Determining Subjective Thresholds for Display Usability Under Combined Whole-Body Vibration Plus G-Loading

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EXECUTIVE SUMMARY

The combined vibration and G-loading that may occur during Ares-I first-stage flight poses challenges to the development of reliable and robust crew interfaces and operations concepts. Although the vibration environment will be well within established human health limits, we do not yet have thorough understanding of or sufficient confidence in the crew's ability to extract and interact with information from proposed Orion "glass" display formats under such potentially harsh conditions.

The present experiments expand upon our previous empirical findings for text readability under vibration and under vibration plus G-loading (Adelstein et al., 2008a,b) by also considering non-alphanumeric forms of information display. From these two new studies, we examined the impact of vibration and of vibration plus sustained 3.8-G loads on observer usability ratings for the three types of flight-display symbology: small (10-pt) or large (14 pt-font) blocks of numerical text; 1-D graphical elements that convey systems-related information (e.g., valve and switch position indicators); and 2-D graphical elements (e.g., attitude display indicators, dials, and trajectory lines).

Participants were instructed to employ a prescribed continuous visual scan pattern to view, in random-ordered succession, three separate display formats that included a primary flight display (i.e., with 2-D elements), a systems summary display (1-D elements), and an alphanumeric display. The viewing of each display format was accompanied by a 55-s whole-body vibration burst that for the first half ramped up in amplitude from ~0.15 to 0.7 $g_{0\text{-peak}}$ and then returned to the starting level by the end of the second half. Participants were trained to categorize each displays' "usability" according to three levels: (A) "usable with no apparent impact from vibration"; (B) "usable but with a noticeable effect of vibration"; (C) "unusable due to vibration." During each burst, participants pressed a response button when they judged that display usability had degraded under increasing vibration from one usability category to the next on the up-ramp and, in reverse, when it improved with decreasing vibration on the down-ramp.

Experiment 1, conducted with thirteen Astronaut Office participants, indicated that usability vibration thresholds were lower for 3.8-G (centrifuge) than for the 1-G (fixed-base) environment. That is, participants were more sensitive (equivalently, less tolerant) to vibration-induced decrements in display usability when the vibration was accompanied by elevated G-loading on the centrifuge. In addition, transition thresholds were significantly lower for 10-pt numeric text than for the graphical symbology on the primary flight and systems summary displays. On average, participants started to note decrements in display usability (i.e. transitions from A to B levels) at vibration amplitudes between 0.33 and 0.42 g, depending on display type.

Post-run analysis of Experiment 1, revealed that, rather than providing a 12-Hz single-frequency sinusoidal input, the vibration waveform in both the centrifuge and fixed-base facilities was corrupted and instead effectively equivalent to a 10-Hz oscillation with 20- and 30-Hz harmonics. In order to determine whether the reported usability thresholds were influenced by these unintended vibration input characteristics, we conducted a second usability study at 1-G bias in the ARC fixed-base vibration chair to systematically examine the impact of the frequency components.

Thus, in Experiment 2, twelve general population participants performed the same usability categorization task as in Experiment 1 while experiencing either the originally intended pure 12-Hz whole-body vibration input, a pure 10 Hz input, or the complex waveform delivered in Experiment 1 (termed "10-prime"). This second study showed usability thresholds increased by an operationally inconsequential 5.6% from the 10-prime to the intended 12-Hz sinusoidal waveforms. For purely sinusoidal inputs, we found thresholds grew by approximately 10% as frequency was increased from 10 to 12 Hz, suggesting our human performance data will be robust to small vibration frequency changes, which may arise due to potential Orion-Ares thrust oscillation mitigations.

1. INTRODUCTION

NASA's Constellation (Cx) Architecture proposes reinvigorating manned space exploration through the development of a new generation of flexible launch vehicles. The architecture selected for the Orion crew launch vehicle reflects a return to a Mercury-Gemini-Apollo-like "capsule" design, but with a larger crew size and modern, more sophisticated interfaces and operations concepts. Returning to an Apollo-era "stack" architecture, Orion will ride into space atop a launch stack consisting of a first-stage solid rocket motor and a second-stage J-2S engine. One of the key design goals of the Shuttle era was to make the "ride" gentler so as to permit teachers and other non-astronauts to travel into space. Thus, Shuttle maximum G-loads were limited to 3.0 G with vibration loads reduced to ~0.1 g. With the return to a pre-Shuttle stack architecture, challenging induced environments not experienced since the Apollo era are now back in the picture. G-loading is expected to peak at 3.8-4.0 Gx nominally on ascent and even higher during re-entry. [Note: Gx refers to the sustained G-load eyeballs in/out, Gy refers to eyeballs side-to-side, and Gz refers to eyeballs up/down. We will use "g" (measured 0-to-peak, which for a single-frequency, single-axis waveform is 1.4 times the RMS, or root-mean-squared value) to refer to vibration level.] Orion vibration specifications for ascent are not yet finalized; but without any imposed mitigation, the actual level will greatly exceed the 0.25 g (at 11 Hz) crew vibration limit specified for Gemini and Apollo (Grimwood, Hack, & Vorzimmer, 1969).

Because vibration is known to impact the accuracy and execution time of visual and manual responses, vibration arising during launch is a critical component of the induced environments to which the crew is exposed during dynamic flight phases. Consequently, it is critical to crew safety and mission success to understand how the vibration from the next generation of NASA launch systems and crew vehicles (Ares-I and Orion, respectively) will affect usability of modern human-system interfaces (i.e., displays and controls).

Over the past 50 years, research worldwide by government, university, and industry labs has provided fundamental descriptions of the deficits in visual and manual performance experienced in various vibration environments, as well as the human health limits for vibration exposure (For a comprehensive summary, see Griffin, 1990). The preponderance of the human performance literature for vibration is concerned with upright seated or standing participants, most often with vibration applied in the body-referenced y- (i.e., side-to-side) and z- (i.e., cephalocaudal or head-to-tail) axes. Also, with the exception of the few studies cited below, most prior research has been conducted under normal earth-gravity environments (1-G sustained G-load). For space launch, however, astronaut crews have been and will be seated in a semi-supine position, with an elevated gravity bias (G-bias) in the body-referenced -x direction (sternum-to-spine) due to the vehicle acceleration pressing the occupant into the seat. The major vibration component arising from the unmitigated thrust oscillation is likely to be directed in the body x-axis, which would be superimposed on to the Gx-bias, the aforementioned G-bias in the x direction.

Human vibration studies specifically addressing the rigors of space launch for the Mercury, Gemini, and Apollo programs were conducted for NASA by the military at Wright-Patterson Air Force Base (WPAFB) and also at NASA-ARC. Specifically, display readability for a semi-supine (i.e., recumbent) participant undergoing vibration in the body x-axis (sternum-to-spine) was examined for a variety of representative vehicle seating configurations by Taub (1964), Faubert, Cooper, and Clarke (1963), Shoenberger (1968), and Clarke, Taub, Scherer, Temple, Vykukal, and Matter (1965). Participants were asked to read dial indicators on rotary "steam-gauge" displays in the presence of 11-Hz vibration (the frequency of concern arising from observed Gemini Titan-II POGO oscillation) while accuracy (error rate) and response time were measured. In most cases, a +1.0 Gx-bias (sternum-to-spine) was provided by orienting the participant chair with its backrest parallel to the ground. An exception is Clarke et al. (1965), who reported dial-reading capability under vibration for a +Gx-bias elevated to 3.85 G in studies conducted on the Ames Five Degree-of-Freedom Simulator (a centrifuge outfitted with a counterbalanced vibration seat). A subsequent report of human-in the-loop study by Vykukal and Dolkas (1966) in the same facility investigated pilot self-rating of dial-reading performance for a Gemini part-task simulation at different levels of x-axis vibration with a concurrent $+G_x$-bias of 3.5 G. A summary of these performance findings, and the resultant operational specifications and levels, are shown in Figure 1.1; additional details and discussion can be found in Adelstein, Beutter, Kaiser, McCann, Stone, Anderson, Renema, and Paloski (2008b).

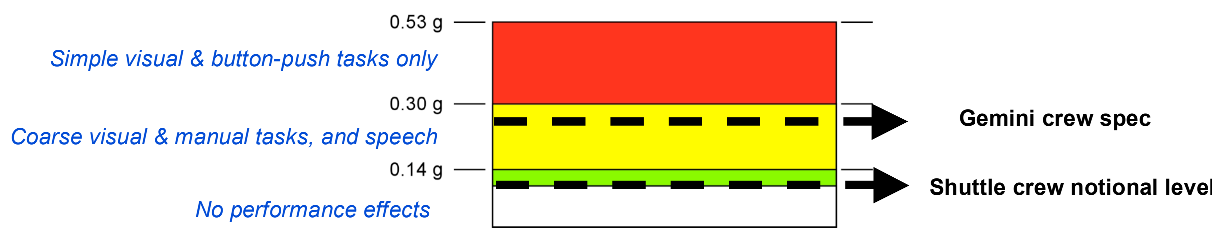


Figure 1.1. Human performance limits from Vykukal and Dolkas (1966), with Gemini specification (0.25 g) and Shuttle notional level (0.1 g measured on the flight deck, inside the console) for comparison.

The interface concepts considered for NASA's next-generation Orion vehicle will differ dramatically from the "steam-gauge" and incandescent lamp displays examined in these historic vibration studies. Orion crews will be reading and processing high-density alphanumeric text mixed with graphical elements rendered on display panels derived from the operational flight-deck hardware of Boeing's 777 and 787 commercial transport aircraft. Effectively, the proposed 1400 X 1050 pixel (11.244 X 8.433 inch) Orion displays are not very different in resolution and size from the Liquid Crystal Display (LCD) panels on modern laptop computers.

A significant barrier to the development and validation of ascent operations concepts is our lack of understanding of the impact of combined vibration and Gx loading on crews' ability to extract information from these modern electronic displays. Considering the content of the advanced (but never implemented) display formats developed for the Shuttle's multifunction electronic displays by the Cockpit Avionics Upgrade (CAU) project, Orion display symbology should fall into three major categories. Alphanumeric symbols (letters, digits, and words) will be used to convey specific flight and systems parameter values, electronic procedures, data labels, and the like. Larger 2-D graphical elements, such as attitude display indicators, dials, and trajectory lines, will populate primary flight displays and provide situation awareness concerning vehicle attitude, position, velocity, and the health of the automated guidance systems. Finally, smaller 1-D graphical elements, such as valve and switch position indicators, will be used to depict the current operational mode and the operational status of onboard engineering systems.

Recently, we examined the combined impact of a target set of vibration levels under 1.0-G (Adelstein, Beutter, Kaiser, McCann & Stone, 2008a) and sustained 3.8-G loading (Adelstein et al., 2008b) on participants' ability to encode and process strictly alphanumeric symbology. Our results showed that, even under sustained 3.8 G, the ability of both general population and Astronaut Office participants to process three-digit strings was relatively unaffected by 12-Hz vibration with an amplitude as high as 0.3 g_x (zero-to-peak). However, considerable and statistically significant levels of performance disruption occurred at 0.5 g_x for small (10-pt font) stimuli, and at 0.7 g_x for both the 10-pt and14-pt font stimuli. The results suggest that the original Gemini-Apollo limit of 0.25 g_x is low enough to support processing of alphanumeric symbology on modern Orion displays.

Reducing Orion cockpit vibration to 0.3 g_x or below, however, may be difficult for Aries-Orion designers to achieve. It is therefore noteworthy that early work on human performance under sustained G and vibration by Clarke and his colleagues (Clarke, et al., 1965), using a rotary dial-reading task, produced results quite different from those obtained with our numerical text-processing task. Clarke at al.'s findings suggests that people's ability to extract and process information from graphically salient 2-D symbology is considerably more resistant to vibration and G-loading than alphanumeric symbology. If confirmed, this could have important implications for both display design and operational concept development. It would suggest, for example, that during periods of peak vibration and G-loading on Orion ascents, crew situation awareness (SA) and operational readiness could be sustained by phase-tailoring ascent displays to replace alphanumeric symbology with larger, graphical symbols wherever possible.

The primary purpose of the studies in this report is to assess the issue of whether vibration has a different impact on usability of the three categories (i.e., alphanumeric, 1-D, and 2-D graphical) of symbology defined above. To investigate this question, in Experiment 1 experienced (Astronaut Office) participants were exposed to a prolonged (55-s) vibration burst while continuously scanning selected elements of a primary flight display, a systems summary display, or a numeric text display that contained multiple sets of the three-digit strings used by Adelstein et al. (2008b). The vibration burst experienced during each display presentation followed the same temporal profile: a gradually increasing ramp-up of the vibration level followed by a gradually decreasing level of vibration. Three "display usability" categories were defined, corresponding roughly to "usable with no apparent impact from vibration (Level A)," "usable but with a noticeable effect of vibration (Level B)," and "unusable due to vibration (Level C)." More details on the definition of these categories are provided below.

At the beginning of the vibration profile, when vibration was constantly increasing, the participants' task was to press a response button (i.e., to "click") when they judged that display usability had transitioned from Level A to Level B, and then to click again when they judged that usability had transitioned from Level B to Level C. On the backside of the profile, when vibration was steadily decreasing, participants made the same judgments in reverse (i.e., Level C to Level B, and then Level B to Level A). In this way, we could obtain objective engineering measurements of the vibration levels that corresponding to subjective thresholds subjective assessments for transitions between these usability categories, and determine whether the thresholds differ for Primary Flight Display Symbology, Systems Summary Display symbology, and alphanumeric symbology. While Vykukal and Dolkas (1966) also collected subjective ratings on display (and control) usability, they presented vibration only at fixed discrete levels and collected multiple numerical (but still subjective) ratings for each vibration level. Effectively, their data were ordinal in nature and, therefore, could only be treated via conservative, nonparametric statistical methods. An advantage of the Method of Limits approach we follow, wherein participants indicate the specific vibration levels at which their vibration ratings cross specified thresholds, is that responses can be characterized on a ratio scale (Stevens, 1951, pp. 23-30) and the data may be analyzed using more powerful parametric statistical techniques.

Several additional questions concerning information extraction in a combined vibration plus G-load environment were also examined. Experiment 1 enabled us to determine the extent to which Astronaut Office participants' *subjective* judgments of alphanumeric readability under vibration reflected of the effects of vibration on their *objective* performance with alphanumeric symbology reported in Adelstein et al. (2008b). Experiment 2 examined the impact of the vibration waveform (frequency and presence of harmonic remnants) on the judged usability of both alphanumeric and graphical displays.

In order to fully validate the subjective ratings obtained in Experiment 1, we needed to draw on the objective reading performance reported in Adelstein et al. (2008b) to determine the extent to which the subjective usability thresholds matched the effects of vibration on the same participants' reading performance with the same alphanumeric display. However, a challenge to making this direct comparison arose when we discovered that the vibration profile used for the subjective ratings task (Experiment 1 of the present report) did not match the vibration profile employed for the objective alphanumeric reading study. Experiment 2 assessed whether the difference in vibration frequency content used in Experiment 1 and in our prior study (Adelstein et al., 2008b) had any bearing on subjective ratings of display usability. In addition to validating cross-study comparisons in the current studies, demonstrating whether vibration in the 10 to 12 Hz frequency range have similar performance impacts could validate the utility of the Gemini era centrifuge plus vibration studies, which were conducted for acceleration waveforms with 11-Hz fundamental frequency content plus substantial harmonic distortion.

Both Experiment 1 and Experiment 2 employed the fixed-base vibration platform in the Intelligent Spacecraft Interface Systems (ISIS) Laboratory at NASA Ames Research Center. Experiment 1 also utilized the NASA Ames 20-G Centrifuge Facility. These facilities are described in the following section and the references cited therein.

2. FACILITIES

Fixed-Base Vibration Platform/Chair

The Fixed-Base Vibration Platform located in the ISIS Lab was used in these studies not only to collect usability rating data under a 1-Gx bias, but also to familiarize participants with the vibration levels they would experience during the test sessions in the centrifuge and train them on the number-reading task reported by Adelstein et al. (2008b). The platform, which comprised the vibration generation components and chair, are more fully described by Adelstein (2008a).

The vibration generation components consist of the actuator and control units of a commercial off-the-shelf home-entertainment chair product (D-Box Technologies, model Quest). The fixed-base vibration platform includes three actuators in a tripod arrangement bolted to a welded steel-tube frame plus the actuators' controller. By selectively activating different combinations of actuators, the D-Box control firmware enables control of displacement (and consequently vibration) in the body x-axis translation, roll rotation about the body z-axis, plus pitch rotation about the body y-axis. The actuator controller is interfaced as a standard USB sound device to a standard Windows personal computer. A padded surgical examination chair was secured in a recumbent orientation via a rigid wooden-box structure bolted to the vibration platform steel-tube frame.

As shown in Figure 2.1, the thickly padded back of the surgical chair employed in our first 1-G study (Adelstein et al., 2008a) was replaced by a thinly padded sheet aluminum reinforced by a structural aluminum frame that more closely matched the structural characteristics of the vibration chair mounted on the centrifuge described below. Headrest-to-seat-pan distance for the revised fixed-base chair was also adjustable, in this case, by simply relocating the foam pad location on the aluminum seat back.

Figure 2.1. ARC Fixed-Base Vibration Platform.

To ensure appropriate coupling between the vibration source and the participant's head, the head was secured to the headrest pad by an adjustable head strap tightened across the forehead. In order to monitor the participant's actual head vibration during the studies, a pair of lightweight (46 grams each) tri-axial accelerometers (Crossbow Technology, model CXL04GP1) were secured in a fixed-geometry configuration to the head restraint strap. Analysis of the head motion data and its correlation with task performance is beyond the scope of the present study but will be performed as part of a later report. Participant location in the seat was maintained by gravity and friction, without need for a body harness.

Details of the specific vibration stimulus profiles employed in these studies will be described in the methods section of Experiment 2. Note that Experiment 1 used a single vibration profile: a complex waveform with a 10-Hz fundamental component plus 20- and 30-Hz harmonics.

Fixed-Base Display and Response Device

For this experiment, the Fixed-Base Vibration Platform was equipped with an overhead LCD monitor and a two-button response device. The display had a 15 in (37.3 cm) diagonal viewing area with a resolution of 1024 X 768 pixels. The display was set to a luminance of 130 cd/m^2 for a saturated white test patch (RGB values: 255, 255, 255) and operated at a refresh rate of 60 Hz. The display was supported above the participant, 18 inches from the "cyclopean" eyepoint, by a rotatable swing-arm that was bolted to its back. Because the table and swing arm were independent of the vibration platform, the LCD monitor did not physically vibrate. The swing-arm allowed the monitor to be rotated away from the participant for unimpeded ingress and egress from the experiment chair.

The display and experiment control program ran on a 2.66 GHz quad-core Dell Precision T3400 under the Windows Vista (32-bit) operating system. A modified hand-held finger mouse, upgraded with two aviation-grade push-button switches, served as the participant's manual response device. The response device was interfaced to the computer via a USB port.

20-G Centrifuge Facility

The Ames 20-G Centrifuge, shown in Figure 2.2, is a 58-foot diameter centrifuge with three enclosed cabs (each 7.6 ft X 5.9 ft X 6.8 ft). This study utilized one of the cabs mounted at the end of the arm (Cab A). The participant faced inward toward the axis of rotation in a chair reclined back so that during study data collection the resultant gravitational vector, Gx, pointed in the chest-to-spine direction, consistent with what is anticipated at the end of first stage flight during an Ares-Orion launch. While the centrifuge has a maximum human rating of 12.5 G, for this experiment, we did not exceed 3.8-Gx as resolved into the seat occupant's body x-axis (3.5 G radial for 20.4 RPM plus 1 G earth gravity). Moreover, we limited G-level ramp-up and ramp-down to an acceleration rate of 0.1 G/s (well below the centrifuge's maximum capability of ~1.0 G/s) in order to minimize the rate of change of rotational acceleration and associated adverse perceptual/autonomic effects.

A wireless Ethernet data bridge provided communication between the onboard computer and the experiment monitor's virtual computer desktop. Video, voice, and medical data were transmitted via a slip-ring assembly above the hub of the centrifuge structure. Areas adjacent to the centrifuge rotunda were available for participant preparation, participant monitoring, pre-and post-centrifugation testing, data collection, and, if necessary, emergency medical procedures.

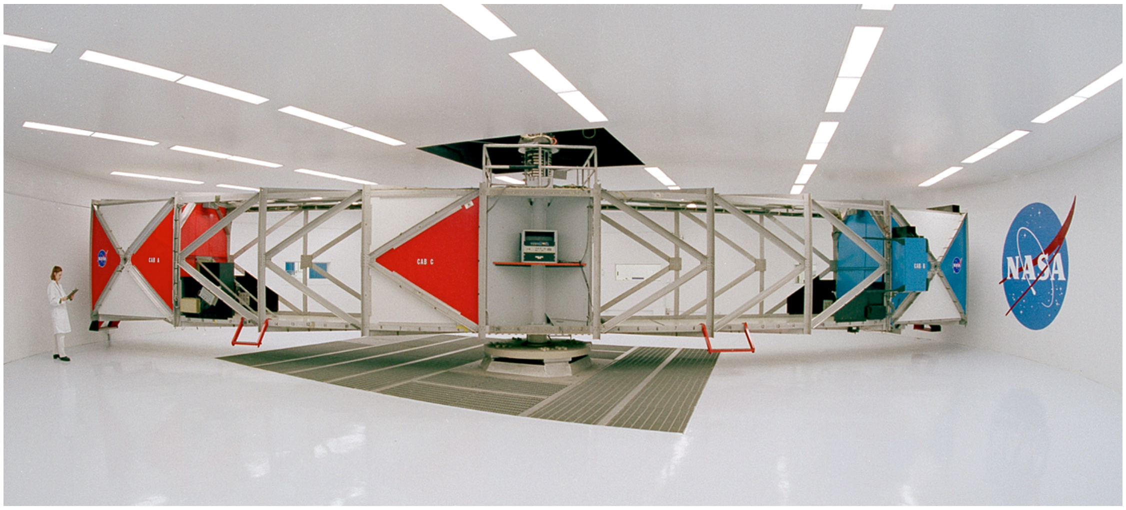


Figure 2.2. ARC 20-G Centrifuge Facility. Cab A is on the far left, closest to the technician.

Centrifuge Vibration Platform/Chair

The centrifuge vibration platform, shown in Figure 2.3, is based on similar actuator and control components from D-Box Technologies, onto which are mounted a custom-built aluminum sheet-metal chair and frame. The centrifuge vibration platform actuator components are larger, higher-force-capacity versions of the products used for the fixed-base portion of the study. Instead of three actuators, the centrifuge version of the platform has four for higher payload capacity, in order to enable operation under heightened G-loading. As in the fixed-base chair, the D-Box control firmware enables controlled translational vibration in the body x-axis and rotational vibration about the body z-axis (roll) and y-axis (pitch). In this study, however, we only employ the x-axis translational capability.

The chair itself was thinly padded, sufficient for participant comfort, but stiff enough to ensure transmission of the commanded actuator vibration to the occupant. The vibration platform was dynamically isolated to prevent cross-coupling of platform vibration with the centrifuge's structural modes. Control of the vibration platform state was implemented from the experiment control computer located in centrifuge Cab B, nearest to the hub in Figure 2.2. Operator monitoring of the on-board control computer was accomplished via a remote "virtual-desktop" window on a separate ground-based computer in the 20-G Centrifuge facility control room.

Figure 2.3. Vibration platform and chair in the ARC 20-G Centrifuge cab.

Participants were seated in a chair on the 20-G Centrifuge located at a nominal radius of 7.85 m (25.75 ft) from the center. They faced inward to the centrifuge's hub, i.e., rotational axis. The chair was tilted back to a fixed angle of 15.3^{o} from upright. The 15.3^{o} seat angle aligned the body x- (sternum-to-spine) axis with the resultant direction of the Earth's 1-G summed with the centrifuge's centripetal acceleration vector specifically at the rotational rate [2.14 rad/s (20.4 RPM) for a nominal occupant radius of 7.85 m (25.75 ft)] necessary to achieve the +3.8 G_x bias for the main study. While the resultant G-vector at the intermediate 1.5-, 2-, and 3-G transition levels did not align with the body x-axis, this discrepancy decreases with increasing acceleration. The discrepancy only existed during the low-G phases of the familiarization runs and during the ramp up to and down from 3.8 G in the main study (during which participants are not performing experimental tasks). This discrepancy caused by the changing direction of the resultant acceleration vector is typically perceived by the participant in the fixed (non-tilting) chair as a change in body pitch angle when the centrifuge rotation rate increases or decreases.

Tri-axial accelerometers (Crossbow Technology, model CXL10GP3) suitable for operation in the centrifuge's elevated G-environment were mounted at key locations on rigid chair structures to enable monitoring and recording of chair vibration levels during all phases of the study. To ensure constant coupling between the vibration source and the participant's head, the head was secured to the seat headrest by an adjustable head strap across the forehead similar to that used on the fixed-base chair. Actual head vibration was measured via a pair of lightweight (46 grams each) triaxial accelerometers (Crossbow Technology, model CXL10GP3) secured in a fixed-geometry orientation to the head restraint strap to allow for a 6 degree-of-freedom reconstruction of head motion. Again, analysis of the head-motion data and its correlation with task performance is beyond the scope of the present study.

Participants were secured in the seat by a five-point safety harness. In their left hand, participants held an emergency signal switch that sounded an alarm to alert the control room monitors and operators whenever they failed to maintain pressure on the switch. Details of the shutdown procedures for both the vibration platform and the centrifuge are delineated in the Safety Procedures approved by the ARC Human Occupancy Review Board (HORB). Additionally, the ARC HORB reviewed and approved all equipment and systems used onboard the centrifuge to be safe for human occupancy.

Centrifuge Display and Response Device

The display monitor used in the centrifuge cab was identical in size and resolution and operated at the same refresh rate and brightness as the fixed-base display. The monitor in the centrifuge cab was mounted on a heavy-duty frame that could be locked in either the normal viewing orientation or upward, as depicted in Figure 2.3, for easy chair ingress and egress. The two-button response devices for the centrifuge and fixed-base facilities were identical.

The on-board experiment control computer housed in Cab B (nearest to the hub) was configured identically to the fixed-base system. The computer was operated in a dual-window mode, supporting both the participant display window in Cab A and the experiment operator's console on a monitor in Cab B. Both Cab A and Cab B displays were mirrored on the virtual desktop at the experimenter's station. The use of virtual desktop architecture had no impact on the update rates of the control program or the participant's display.

3. EXPERIMENT 1 – ASTRONAUT OFFICE RATINGS OF DISPLAY USABILITY

We relied on the experience and expertise of Astronaut Office volunteers to determine subjective usability thresholds for three distinct types of display symbology under different combinations of G-loading and vibration. One type was the 10-pt and 14-pt numeric display (see Figure 3.2 in the "Stimuli" subsection below) that was used by Adelstein et al. (2008b) to objectively measure participant number-reading performance. The inclusion of these numeric displays in the present study enables us to re-assess the impact of vibration and sustained G, but this time from the standpoint of subjectively assessed usability.

The second display (see Figure 3.3 in the "Stimuli" subsection below) incorporated elements of the Shuttle Cockpit Avionics Upgrade's (CAU's) Primary Flight Display (PFD) and Horizontal Situation Awareness (H-SIT) display formats, permitting us to assess usability of the large, typically 2-D graphical symbols used on flight-related display formats.

The third display (see Figure 3.4 in the "Stimuli" subsection below) was another CAU hybrid. The top half of the image depicts of the helium supply system for the Shuttle's three main engines from the CAU's main propulsion system (MPS) display format. The bottom half shows the propellant feed lines and other subsystem elements of the Shuttle's Orbital Maneuvering System (OMS) from the CAU's OMS system summary display format. With its preponderance of graphical symbols such as valve position indicators and gaseous flow lines, this OMS/MPS display allowed us to assess the usability of systems-related forms of 1-D graphical symbology.

The Display Rating Task. In an adaptation of the well-known psychophysical "method of limits," each display was viewed continuously during a vibration "burst" profile that lasted ~55 s. Each ramp started at a low, 0.2 $g_{0\text{-peak}}$ (zero-to-peak) vibration, increased steadily up to a maximum of 0.7 $g_{0\text{-peak}}$, and then decreased steadily back to ~0.2 $g_{0\text{-peak}}$. The ramp-up and ramp-down portions of each profile both lasted ~27 sec. The 0.2 $g_{0\text{-peak}}$ starting and ending vibration magnitudes were seen in our prior studies (Adelstein et al., 2008a,b) to be below the level at which statistically discernable text reading decrements occurred.

For each display, we specified a visual scan pattern for participants to employ throughout the course of the vibration ramp-up and ramp-down. The scan pattern was designed to encompass selected subsets of display symbology in a particular order. For the two graphical displays, each element in the scan provided a piece of information that, when integrated with the information provided from the other scanned elements, provided relatively complete situation awareness (SA) either about the state of the vehicle at a distinct point in a nominal ascent trajectory (i.e., "roll to heads-up" from the PFD in Figure 3.3), or about a particular off-nominal operational configuration for the OMS and MPS systems during ascent (Figure 3.4). For the numeric text display, participants were instructed to examine (i.e., identify) all the individual digits of one three-digit string (i.e., triplet) and before proceeding to examine the next triplet.

In addition to following the specified scan patterns, participants were instructed to continuously judge, as vibration first increased and then decreased, how difficult it was to perform their scan and maintain situation awareness of the numeric strings or of overall vehicle/system state depicted on the respective static display format. Three levels of scanning difficulty were defined for the participants. *Level A*, at which participants judged that there was no noticeable impact on their scan and overall SA, was the starting level for each display viewing vibration, and typically corresponded to the mild vibration at the beginning and end of the vibration burst. At *Level B*, participants judged that, although the scan still supported an acceptable level of SA, there was a noticeable increase in scanning difficulty but the scan could still be performed by exerting more effort. In other words, this level corresponded to the vibration intensities over which participants could still compensate for the vibration-induced difficulty. *Level C* encompassed vibration intensities that forced participants to spend so much time attempting to acquire information from individual elements that the overall scan pattern was completely disrupted, and an adequate level of SA could not be maintained.

While participants were not judging actual vehicle handling characteristics, they were instead *estimating* the extent to which the degradation in display usability would impact vehicle control or systems diagnostics. Thus, in effect, the impairments associated with the A, B, and C judgment levels are akin to those describing the major categories (i.e., I, II, and II) of the Cooper-Harper (C-H) rating of handling characteristics (Cooper & Harper, 1969).

Drawing on this analogy with the Cooper-Harper rating method, the formal definitions of the three judgment levels provided our participants borrows from the C-H terminology as follows:

- Level A (akin to C-H category I with ratings 1, 2, and 3): display readability (i.e., participants' display scanning) is unimpeded and performance would be deemed satisfactory without need for improvement;

- Level B (akin to C-H category II with ratings of 4, 5, and 6): display readability (i.e., participants' display scanning) is noticeably impaired though still usable, but performance is deficient warranting improvement;

- Level C (akin to C-H category III with ratings 7, 8, 9, and 10): the display is unreadable, participant scanning is completely disrupted, and visually guided performance is impossible.

Participants indicated their judgments by pressing buttons on the handheld response device to mark the instant at which their rating of display usability transitioned between the three aforementioned scan/SA disruption levels (i.e., from A to B and then B to C as the vibration ramped up, and then back from C to B and, finally, B to A as the vibration ramped down). Importantly, none of the button presses was mandatory. For example, if, during the ramp up, a participant determined that display usability never deteriorated from Level B to Level C, then he or she simply did not make a second button press. In such a case, there could only be a button press from Level A to Level B on the ramp back down. Moreover, there was no requirement that participants make the same number of button presses during the descending as the ascending portion of the vibration burst—i.e., they could end the particular display format viewing at Level B.

A schematic of the ramp sequence, including the participant's indicated transition points and the corresponding Cooper-Harper-like levels, is provided in Figure 3.1. Note that the vibration amplitudes at A-B and B-C transitions are higher than the respective amplitude for B-A and B-C transitions. This response hysteresis pattern (transition judgments to ascending stimuli occurring at higher levels than the reverse transitions for descending stimuli) is typical of method of limit psychophysical testing and was also true for the data collected in the present studies.

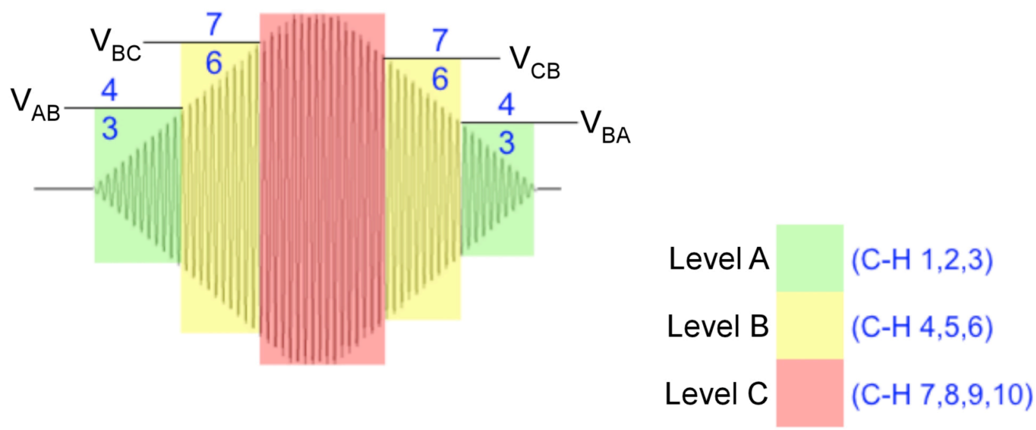


Figure 3.1. Ascending and descending vibration transitions marks. (Cooper-Harper scale rating equivalents are indicated in blue text.)

The following critical questions were addressed in this first experiment:

1. Across participants, what are the average Level A-to-Level B and Level B-to-Level C vibration thresholds?
2. Do these subjective thresholds differ among the three display types (and, hence, across the three categories of symbology), and across the two font-sizes for the alphanumeric display?
3. Does the combination of sustained (3.8) G and vibration yield different thresholds than vibration alone?

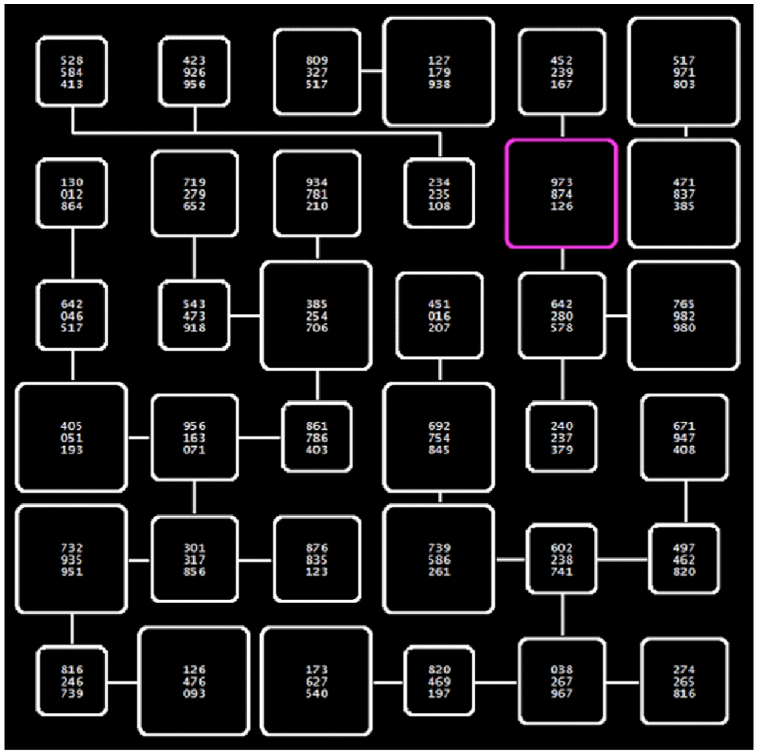
Methods

<u>Participants</u>
Thirteen (10 men and 3 women) members of the Astronaut Office at the Johnson Space Center (JSC) agreed to participate in this study following a briefing that outlined the study's goals and participants' commitments and risks. During the centrifuge sessions, a JSC flight surgeon monitored participants' well being via closed-circuit video camera, voice communications, and blood oxygen saturation pressure measurements. (The flight surgeon was also on-call for the fixed-base sessions). None of the participants elected to terminate any of their familiarization or test sessions, nor were any sessions terminated for medical reasons.

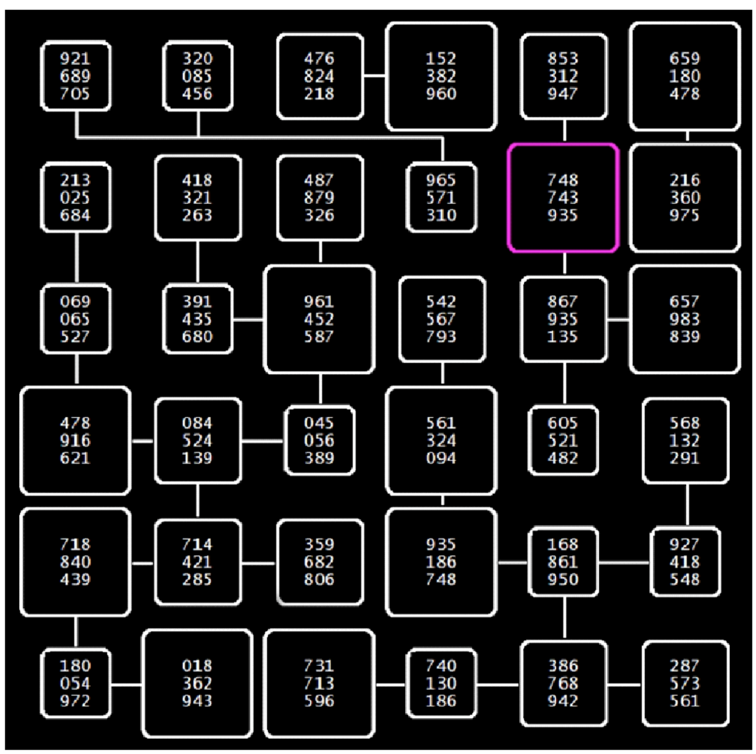
<u>Stimuli</u>
Three displays format types, representative of alphanumeric, 1-D, and 2-D graphical categories, were used.

Alphanumeric Display (Numeric Text). All digits in the text display (Figure 3.2) were drawn in either 10- or 14-pt Lucida Console, a sans serif non-proportional font. At a viewing distance of 18 inches, the 10-pt font targets subtended 0.44° of visual angle vertically and 0.88° horizontally while the 14-pt font digits subtended 0.62° of visual angle vertically and 1.24° horizontally. Measured from the mid-point of each display, the distance to the far edge of the outermost box was 14 degrees of visual angle in both the horizontal and vertical directions. With one exception (the box housing the target), all boxes, lines, and digits were drawn in fully saturated white (RGB values: 255, 255, 255) at a brightness of 130 cd/m^2 against a black background (RGB values: 0, 0, 0) at a brightness of 0.3 cd/m^2. The box surrounding the target was drawn in magenta (RGB values: 254, 0, 220). Seven participants rated the 10-pt font and six the 14-pt numeric displays.

For this stimulus, participants were instructed to begin their scan by identifying (reading) the digits in the middle row of the magenta colored box, then shift to the box adjacent on the left and read the middle row there. They were to continue scanning in an S-pattern across all boxes in the display, reading each middle row in turn.



(10 pt)



(14 pt)

Figure 3.2. Numerical display format.

PFD Display (2-D Graphics). The PFD display (Figure 3.3) comprised primarily candidate primary flight display (PFD) Shuttle symbology that was designed as part of the Shuttle CAU. As shown in the figure, this display format comprised an assortment of gauges, indicators, dials, and tapes. The arrangement of the symbology was altered slightly from the original CAU PFD candidate design, with some of the display elements omitted to instead incorporate the trajectory line with the Shuttle "bug" (ring) and predictor "dots" from the CAU vertical trajectory display format. The PFD Display stimulus subtended 28° of visual angle vertically and horizontally.

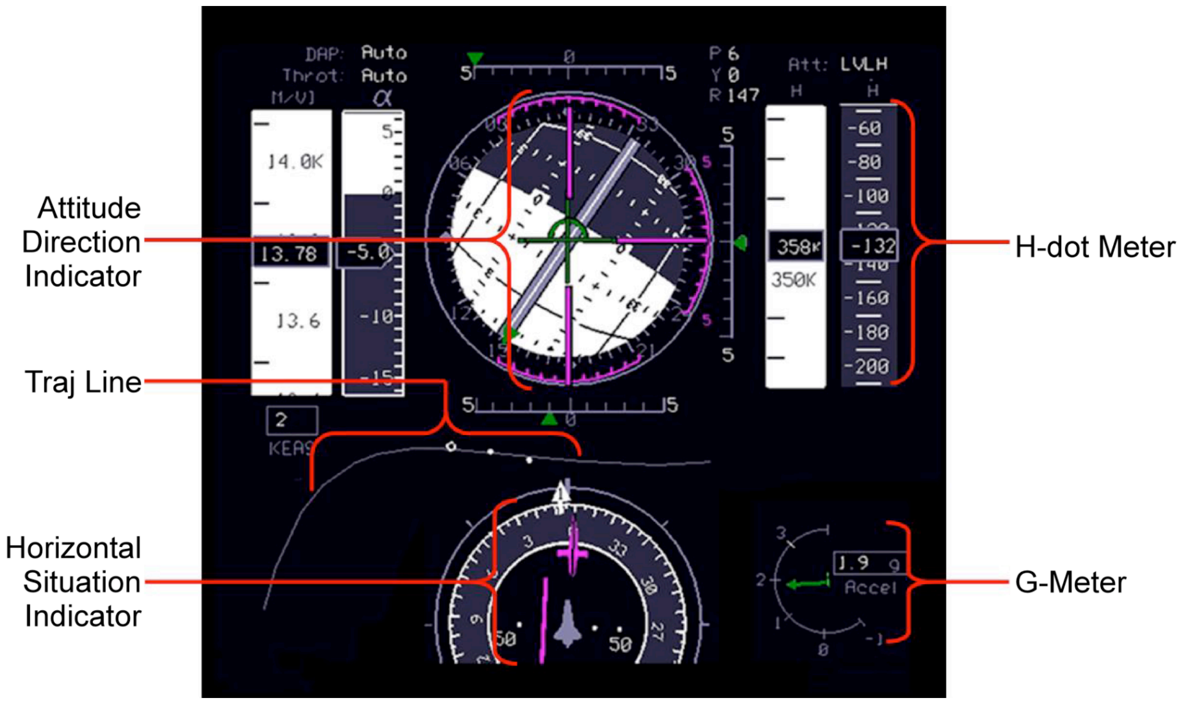


Figure 3.3. Primary Flight Display format. (Red brackets and lines are not part of the display format, but were added to annotate the figure.)

During actual ascent, flight displays are, of course, quite dynamic. Because we did not want to confound differences in vibration level over the course of the burst with differences in display content, we utilized a static "snapshot" of the display elements as they appear at exactly 5 min 40 s into a simulation of a nominal Shuttle launch. This particular time was selected because at this instant the Shuttle is rolling from a "heads-down" to a "heads-up" attitude, placing many display elements, such as the large 2-D attitude display indicator, in a distinctive visual configuration. Participants were instructed to incorporate the following display elements into their scan: the H-dot Meter, showing negative (dark background) vertical velocity; Attitude Directional Indicator (ADI) including the three magenta attitude error needles; Shuttle position bug and predictor dots on the vertical trajectory ("traj") line; the Horizontal Situation (H-SIT) Indicator, showing a slight sideslip error; and the G-meter, showing a sustained G level approaching 2.0-G. For this display, participants were explicitly instructed to exclude any alphanumeric symbology in their scan or usability assessment.

Systems Display (1-D). The systems display, shown in Figure 3.4, comprised symbology representative of that to be included in the Orion systems monitoring and systems management display formats. Crewmembers use such symbology to understand the current operational mode (configuration) of an onboard system, determine whether a current operational mode is nominal or off-nominal, and to troubleshoot systems malfunctions. The top half of the display consisted of the upper region of the CAU project's candidate Shuttle Main Propulsion System (MPS) Summary Display. This region included symbology depicting the helium supply tanks, feed lines, interconnect lines, left and right leg isolation valves, and main engine thrust indicators looking as they would in a nominal full throttle situation. While the center and right helium supply system configuration was depicted as fully nominal, the left engine configuration was not. For the left main engine, the left leg isolation valve was closed, there was no flow through the left leg, and the interconnect valve was open. The lower half of this display consisted of a section of the CAU's Shuttle Orbital Maneuvering System (OMS) Summary Display, which included graphical representations of the nitrogen supply tank and feed line, solenoid valves, bipropellant valve assembly, fuel and oxidizer inlet pressure gauges, and engine thrust indicators. These elements were in a nominal configuration for an active (firing) right OMS engine, and a non-firing (inactive) left OMS engine. The Systems Display subtended 28° of visual angle.

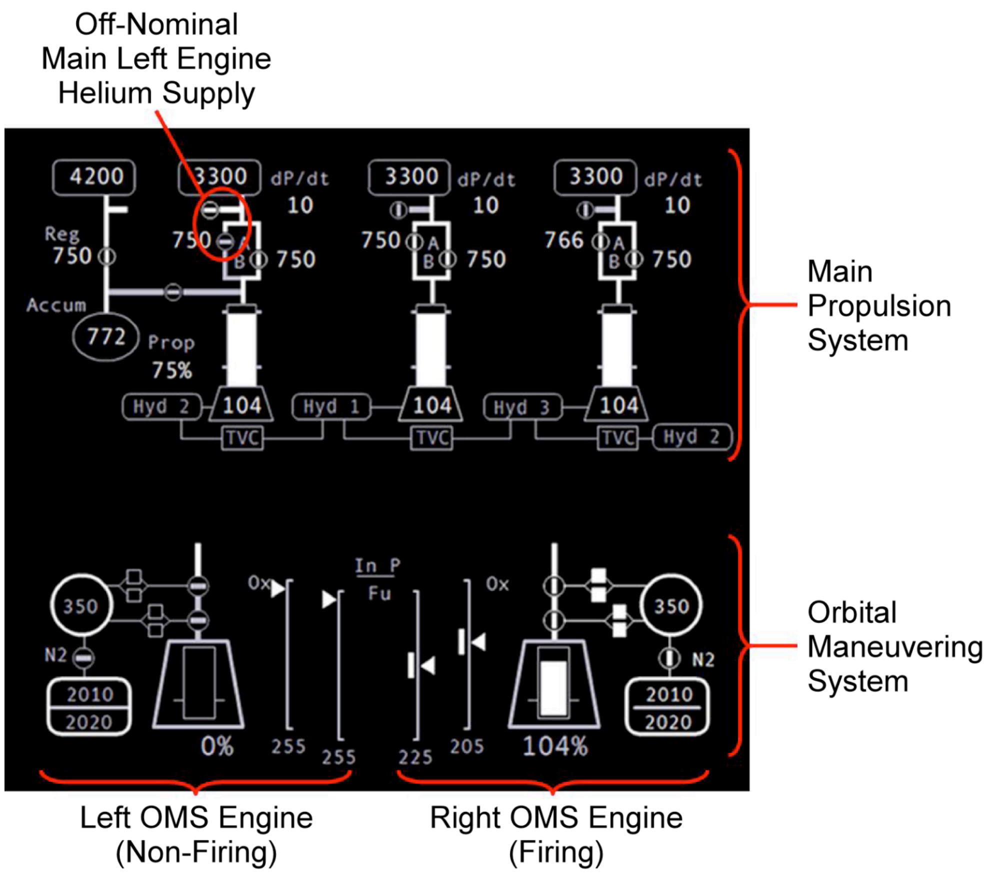


Figure 3.4. Orbital Maneuvering/Main Propulsion Systems display format. (Red brackets and lines are not part of the display format, but were added to annotate the figure.)

Participants were instructed to include in their scan all elements necessary to maintain situation awareness of the main engine helium supply system configuration (including the off-nominal configuration of the left engine), a nominally firing right OMS engine, and a nominally quiescent (non-firing) left OMS engine. Just as for the PFD format, participants were explicitly instructed not to include any of the alphanumeric symbology in their scan or usability assessment.

Procedure.

Usability ratings were collected over two days. On Day 1, participants were familiarized with the vibration environment and then trained to perform the usability task on the fixed-base platform in the vibration-only (1.0-Gx bias from Earth gravity) environment of the ISIS Laboratory. Following vibration familiarization and training, a full set of rating data for each display format was collected while experiencing vibration ramps at a 1.0-G bias. Later on Day 1, participants proceeded to the ARC 20-G Centrifuge facility to undergo their familiarization and training for exposure to Ares-Orion maximum 3.8-Gx loading. On Day 2, a second set of rating data was collected from the participant for each display format under the same vibration conditions, but this time while at a sustained 3.8 Gx on the centrifuge.

Familiarization and Training on Fixed-Base Platform. Upon arrival at the ISIS Lab, each participant was given a written and verbal explanation of the display usability assessment task. Participants then positioned themselves in the chair (see Figure 2.1). The experiment monitor tightened the head strap around their forehead. Next, the participant was exposed to 35 s of vibration at 0.15, 0.3, 0.5 and 0.7 g (0-peak), the continuous vibration levels employed in the subsequent 20-G phase of a separate numeric text reading study (Adelstein et al., 2008b). This 0.7 g familiarization level corresponded to the maximum vibration amplitude to be experienced in the present display usability rating study.

During the display-rating training and practice session that followed, participants completed three separate ratings blocks. During each block, the participant viewed the three different display formats with each participant's fixed order of display presentation assigned according to a quasi-random Latin Square (Williams, 1949). A separate vibration up- ramp/ down-ramp profile was provided for each display format, with the three profiles during the block separated by a 1-s vibration-free interval, as shown in Figure 3.5. After the block's third profile ended, the experiment monitor waited to receive participant consent before proceeding to the next block. The participants' head-restraint strap was released following completion of the third block.

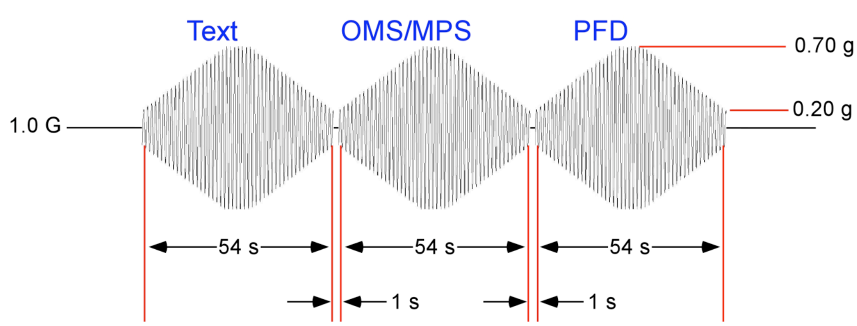


Figure 3.5. Sample training/test block of three trials for fixed-base (1.0 G) runs. Display order was counterbalanced across participants.

Test Run on the Fixed-Base Platform. The test session consisted of three blocks of three display-rating trials. The order in which each participant viewed the displays was with the same as their order in the training session.

On each trial, for each of the three separate displays, participants clicked a response button to signal transitions from one display usability level (category) to another during vibration ramps. To help remind participants of their currently judged usability level, two visual cues, a colored square and a color-coded written message, were inserted into the bottom of each display format (see Figure 3.6). The color of the square indicated the current usability category (green for Level "A"; yellow for Level "B"; and red for Level "C") while the color and content of the text message indicated which category would be selected upon the next response-button press.

For the sequence shown in Figure 3.6, the square is green (signaling the current status is Level "A"), and the message reads "Click at Level B" in yellow lettering at the onset of each vibration ramp. When the first button press is recorded, the square changes to yellow and the message changes to "Click at Level C" in red letters. When the second press is recorded, the status prompts are removed until the peak vibration level is reached. At maximum vibration, the entire display format is blanked for 2 s and the message "MAX VIBE" appears, after which a red square and the message "Click at LEVEL B" in yellow letters appear. On the ramp-down, the first button press changes the square back to yellow, and is accompanied by a "Click at Level A" message in green. The second button press, signaling a return to Level "A" in judged usability, removes the prompts from the display.

The exception to this pattern occurs on trials where participants click only once on the way up (i.e., they never judge display usability as deteriorating from Level B to C as vibration is increased). In this case, the yellow square with red "Click at Level C" message is instead replaced when the display format reappears after maximum vibration by a yellow square and green "Click at Level A" message.

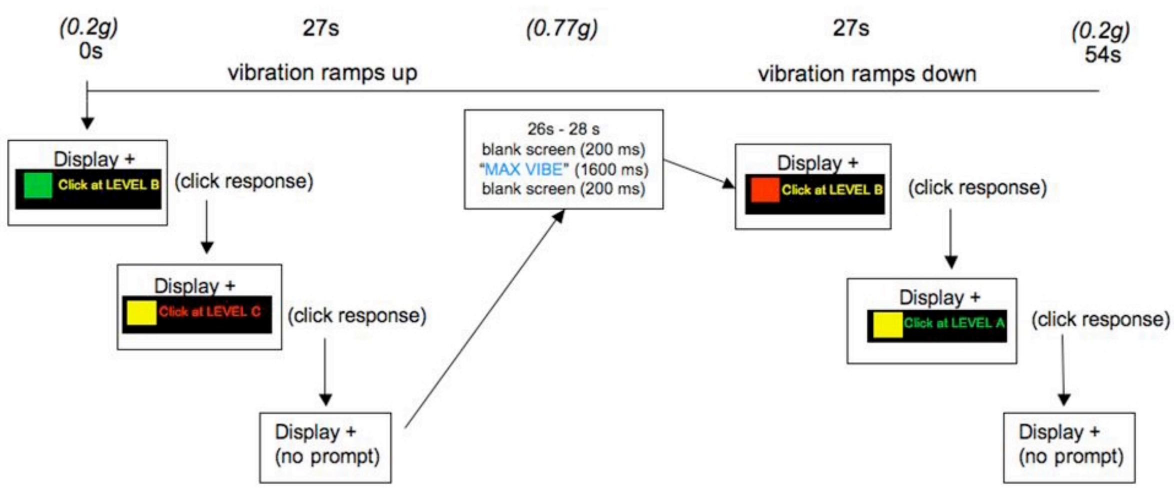


Figure 3.6. Sequence of visually displayed instruction cues during a trial in which the participant indicated A-to-B and B-to-C transitions in usability ratings as vibration increased followed by C-to-B and B-to-A transitions as vibration decreased.

Centrifuge Familiarization Runs. Following the fixed-based portion of the study, participants underwent familiarization and training in the 20-G Centrifuge. Prior to starting the familiarization runs, participants positioned themselves in the seat with the aid of centrifuge operations personnel who adjusted and secured the harness restraint systems (see Figure 2.3) and any medical monitoring equipment (typically only an O_2 saturation sensor for Astronaut Office participants). One of the vibration study monitors tensioned the head restraint strap across the participant's forehead to ensure continuous contact between the participant's head while maintaining sufficient comfort and then aligned the triaxial accelerometer assembly with respect to the midline of the head. Finally, the participant received instructions on 20-G Centrifuge emergency egress procedures (including seat harness and head restraint release) from the centrifuge staff.

After all adjustments were completed and study monitoring centrifuge operations personnel had left the centrifuge, each participant was exposed to increasing levels of G-load up to the experimental level of 3.8 G, to ensure they could tolerate this test environment. (Appropriate to their background with elevated G environments, Astronaut Office participants typically paused at 1.5 G or 11 RPM and then proceeded directly to the full 3.8 G level at 20.4 RPM.) Acceleration rates of change were limited throughout to 0.1 G/s.

As noted above in Section 2, because of the fixed 15.3^{o} seat angle, the resultant G-force vector varied in body-referenced coordinates according to the centrifuge rotational rate. Earth's gravity provides predominantly a body-referenced z-axis (cephalocaudal or head-to-seat pan) component when the centrifuge is at rest, such that the (Gx, Gz) accelerations are (0.25, -0.97). The body-referenced z-axis component was not eliminated until the centrifuge reached its targeted 20.4 RPM rotational rate (i.e., when the exact 3.8 Gx acceleration was achieved).

The participant and medical monitor together decided whether to continue to the next step by considering any observed difficulty or discomfort of the prior step. Had signs or symptoms of unusual stress been encountered, either the participant or the medical monitor could stop the trials immediately. (None of the Astronaut Office participants terminated the study, with all completing their familiarization and data collection runs.)

Following a brief rest period, participants next underwent a centrifugation plus vibration familiarization run. The time course ("G profile") of this familiarization run is illustrated in Figure 3.7. The underlying centrifuge G-level began with a 30-s period at 1.5 G, followed by three 245-s "humps" at the test level plateau of 3.8 G. The humps were separated by a 150-s recovery period at 1.5 G. In order to allow for the stabilization of participants' vestibular system, the first 45 s interval of each 3.8 Gx plateau offered a vibration-free washout period.

In the first hump, the washout period was followed by a sequence of four 45-second vibration periods, each with a constant vibration level (0-to-peak amplitude: 0.15, 0.3, 0.5, 0.7 g). This was followed by an additional 20 s at zero vibration, after which the centrifuge ramped down. The purpose of the first hump was to familiarize participants with the vibration levels to be used in the numerical text reading study (Adelstein et al., 2008b).

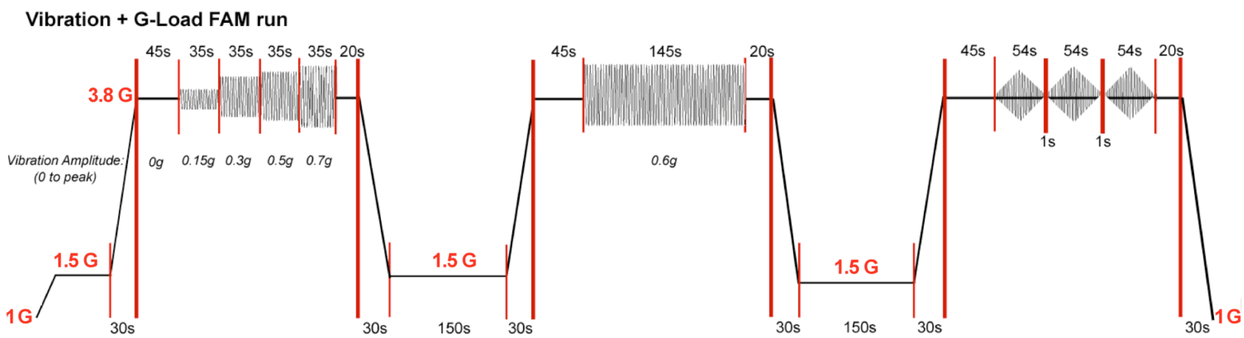


Figure 3.7. G-load plus vibration familiarization run. The third "hump" gave participants the opportunity to practice the display-rating task.

Upon the participant's and the medical monitor's verbal concurrence, the run continued to the second hump. For the second hump, the washout period was followed by 0.6 g vibration at 12 Hz and concluded again with 20 seconds of zero vibration at the conclusion of which the centrifuge ramped down to 1.5 G for 150 s recovery period. During this vibration and 20-s follow-up interval, participants were encouraged to practice the number-reading task for the study reported by Adelstein et al (2008b).

Again after the participant's and medical monitor's verbal concurrence, the familiarization run proceeded to the final hump, during which the participant practiced the display-rating task for the present study in a sequence identical to their actual experimental block. Following the washout period, as depicted in Figure 3.8, participants experienced three consecutive vibration up-down ramps, one for each display format. As noted above, the presentation order of display formats was held constant for each participant throughout the fixed-base and centrifuge familiarization and data collection runs and was counterbalanced across participants according to partial Latin-Square design. For example, a participant assigned to a Text-OMS/MPS-PFD order would see the same sequence, shown in Figure 3.8, during all training and data collection blocks.

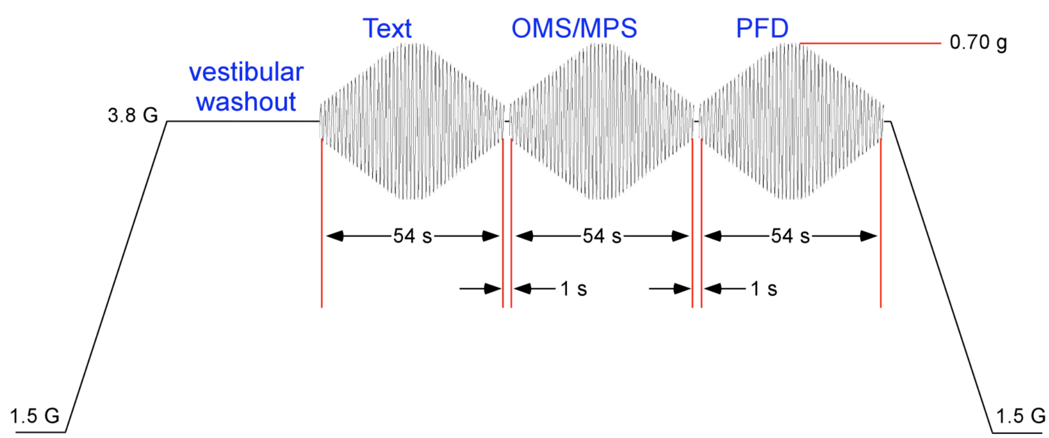


Figure 3.8. Sample training/test block of three trials for centrifuge runs. Display order was counterbalanced across participants.

Following the third (i.e., display-rating practice) block, the centrifuge slowed to a complete stop. As with the centrifuge-only familiarization run, all centrifuge accelerations and decelerations were limited to 0.1 G/s. Once the centrifuge was stopped, the participant was escorted from the cab by the operators, examined by the medical monitor, and debriefed by the experimenter, completing their first study day.

Centrifuge Test Run. Participants returned on the next day for the present display reading study data collections runs as well as those for the numerical text reading study (Adelstein et al., 2008b). They completed all runs for one study before proceeding to the next, with the order of their participation in the separate studies balanced across participants. There was a minimum 1.25 hour rest and debrief period between participants' completion of the first study's runs and the start of the second.

Other than the addition of the 45-s washout period added to the start of each block, the procedure for the display-rating task in the centrifuge was identical to the procedures in the fixed base (vibration only). Thus, each block was structured as the sequence of three triangular one-minute ramps illustrated by Figure 3.8. After the third up-down ramp, the screen was blanked, and the centrifuge slowed to 1.5 g for an inter-block, 150-s vibration-free recovery period.

While the inter-block recovery period could be lengthened at the discretion of the participant, medical monitor, or study principle investigator, this request was never made. And as noted above, a trial could be terminated immediately if signs or symptoms of unusual stress were noted by either the participant or the medical monitor. All participants, however, completed their test blocks without incident.

Results

The vibration level for each button-press response indicating judged transition from A-to-B and from B-to-C during ramp-up and in the reverse direction during ramp-down was quantified in terms of x-axis acceleration (after subtracting out the quasi-static DC component) from the chair accelerometer closest to the headrest, averaged over the interval beginning 0.5 s (i.e., 100 samples at 200 samples/s data acquisition rate) before and ending 0.5 s (100 samples) after an individual button press.

If a participant failed to make a second press on a ramp-up (i.e., no B-to-C transition indicated), the prompt sequence was altered, omitting the C-to-B transition. Assuming the participant indicated a B-to-C on at least one of the other replications of this condition, a vibration level equal to the RMS acceleration from the ±0.5 s surrounding the maximum of the chair vibration envelope was assigned. If a participant missed the final button press (i.e., B-to-A), then a level equal to the RMS acceleration of the final 1 s of chair vibration was assigned.

The resulting vibration levels were averaged across the three repetitions of each display format separately for each of the four transition button presses (i.e., resulting in 12 separate averages). As traditionally done when quantifying psychophysical thresholds, method-of-limit judgments were averaged across the ascending and descending stimulus ramps, combining A-to-B with B-to-A responses and B-to-C with C-to-B responses to estimate, respectively, the AB and BC transition levels for each condition (display-type X test-facility). Consistent with the reasoning underlying this traditional approach, an analysis of the differences between transitions for the ascending and descending pairs (i.e., AB-BA and BC-CB) indicated a systematic positive bias, attributable to a constant subjective hysteresis when rendering judgments of vibration amplitude. This hysteresis effect can be attributed to a systematic ~1.5 s delay in participant button responses on both the ramp-up and ramp-down portions of the vibration profiles for all display formats.

Figure 3.9 shows mean (± standard error of mean) RMS vibration levels for the AB and BC transitions collected on the 20-G Centrifuge and on the fixed-base platform for the two graphical display formats (PFD and OMS/MPS) that were evaluated by all 13 Astronaut Office participants. As discovered post-experiment, the vibration input provided in this study, Experiment 1, was not a pure 12-Hz sinusoid but rather a multi-frequency composite waveform with a 10-Hz fundamental frequency, which we denote as "10-prime." Therefore, in addition to the overall multi-frequency 10-prime RMS levels (left vertical axis), vibration levels are converted to an equivalent 12-Hz response (right vertical axis) by: 1) using a 1.056 scaling factor derived from Experiment 2 (the general-population validation study in Section 4); and 2) subsequently multiplying by 1.414 (square-root of two) to convert the 12-Hz-equivalent response level to g in zero-to-peak units. This conversion enables comparison of the presents results against those obtained under the discrete 0.15, 0.3, 0.5, and 0.7 $g_{0\text{-peak}}$ for true single-frequency 12-Hz vibration in our previous display readability studies (Adelstein et al., 2008a, b). A more thorough description of the 10-prime waveform and its consequences is provided below in Section 4.

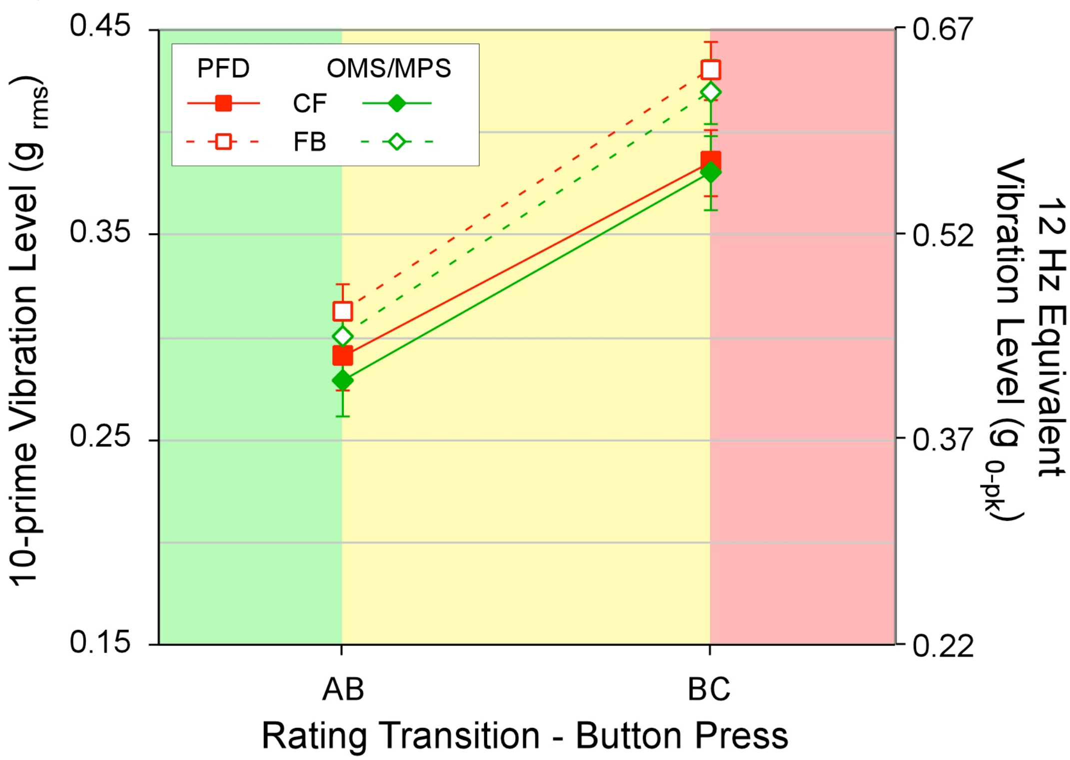


Figure 3.9. Graphical display usability transition levels for vibration superimposed on 3.8 Gx at the 20-G Centrifuge (CF, hollow marks) and 1 Gx on the fixed-base platform (FB, filled

marks). PFD denotes the Primary Flight Display format; OMS/MPS is the combined Orbit Maneuvering System/Main Propulsion System display format.

Figure 3.10 shows mean (± standard error of mean) vibration levels at AB and BC from the centrifuge and fixed-base vibration platform for the two numerical text formats. In this case, the plot combines data from the separate subgroups of six and seven Astronaut Office participants who respectively viewed the 14- and 10-pt versions of the numerical displays.

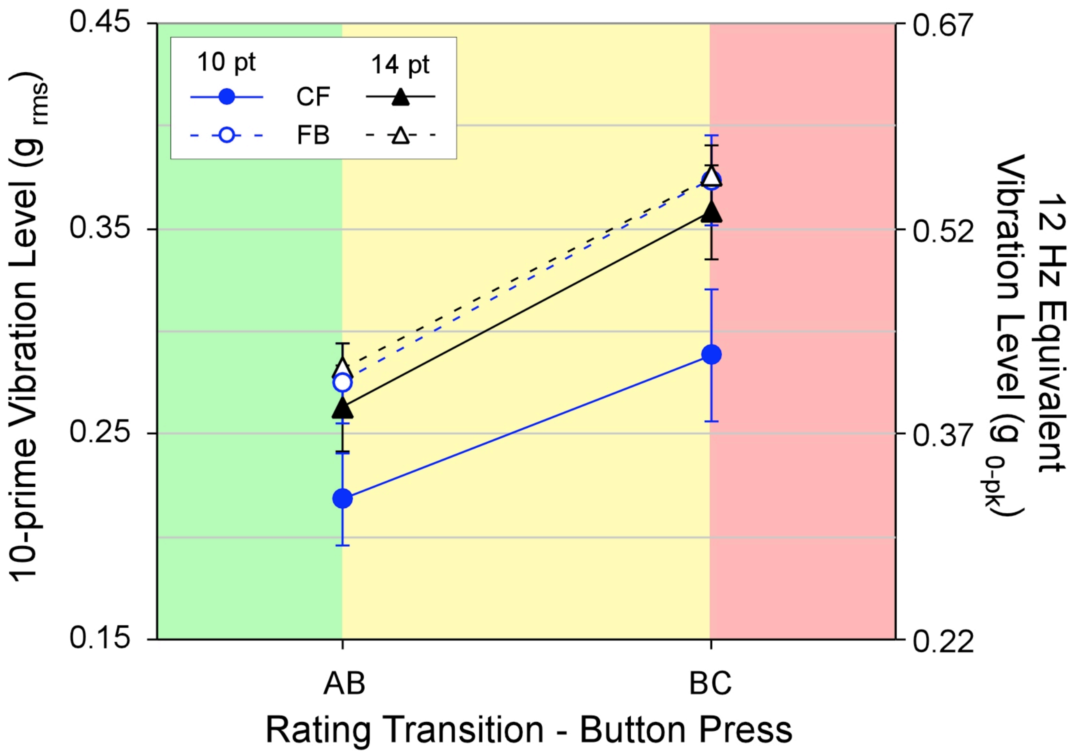


Figure 3.10. Text display usability transition levels for 10- and 14-pt numerical formats under vibration superimposed on 3.8 Gx at the 20-G Centrifuge (CF, hollow marks) and on 1.0 Gx on the fixed-base platform (FB, filled marks).

We conducted a planned contrast (paired t-test), comparing data between the fixed-base (1.0 Gx) and the centrifuge (3.8 Gx) portions of the study. Collecting the vibration magnitudes at the two response levels (AB and BC) for each of the display types viewed (three per participant), indicates a highly significant effect of the centrifuge in lowering tolerance to vibration in terms of participant assessment of display usability (11% reduction; $t_{77} = 5.34$, $p < 0.0001$, two-tailed). Equivalently, this result demonstrates that the centrifuge led participants, on average, to judge displays less usable for a given commanded vibration level. Table 3.1 shows the breakdown of the vibration facility effect by display type, again combining data for the AB and BC response levels. Table 3.1 reports vibration levels after conversion from the RMS vibration appropriate to the composite 10-prime waveform under which these data were collected to the 12-Hz-equivalent zero-peak level. The decrements in judged usability for the PDF, OMS/MPS, and 10-pt text formats are significant, while that for the 12-pt text were not.

Table 3.1 Within-display contrasts between 1- and 3.8-G (12-Hz-equivalent vibration)

	Vibration at combined AB+BC transitions (12-Hz-equivalent)			
Display	**1-G**	**3.8-G**	**Decrease**	**t_{df}, p (two-tail)**
PFD	0.555 $g_{0\text{-peak}}$	0.505 $g_{0\text{-peak}}$	9.4%	$t_{25} = 2.85$, $p < 0.009$
OMS/MPS	0.537 $g_{0\text{-peak}}$	0.492 $g_{0\text{-peak}}$	8.8%	$t_{25} = 2.27$, $p < 0.03$
10-pt text	0.484 $g_{0\text{-peak}}$	0.378 $g_{0\text{-peak}}$	24.6%	$t_{13} = 5.23$, $p < 0.0002$
14-pt text	0.492 $g_{0\text{-peak}}$	0.463 $g_{0\text{-peak}}$	5.9%	$t_{11} = 1.80$, $p < 0.2$ ns

Separate analyses were conducted for the 1-G and 3.8-G facilities to assess whether there were differences between in the transition vibration levels resulting from display format. Due to the mixed experiment design (all participants viewed the PFD and OMS/MPS displays but were separated into either 10- or 14-pt text groups), separate ANOVAs were necessary for each font-size group. Thus, two ANOVAs were performed for the seven participants who viewed the 10-pt text, PFD, and OMS/MPS display formats, with two more for the six participants who viewed the 14-pt text, PFD, and OMS/MPS display formats.

All four ANOVAs demonstrated significant main effects ($p < 0.0003$) for the differences between AB and BC transition levels that are obvious in Figures 3.9 and 3.10. Additionally, the two ANOVAs for the 1-G facility (i.e., fixed-base) both demonstrated a significant main effect of display format (10-pt group: $F_{2,12} = 7.706$, $p < 0.007$; 14-pt group: $F_{2,10} = 5.392$, $p < 0.03$), but no significant interactions between format and AB/BC transitions. For the 3.8-G (i.e., centrifuge) facility, the main effect of display format was significant for 10-pt group analysis ($F_{2,12} = 23.85$, $p < 0.0001$), but only marginal ($F_{2,10} = 3.696$, $p < 0.063$) for the 14-pt group. For the centrifuge facility, only the 10-pt group showed a significant interaction between display type and AB/BC transitions ($F_{2,12} = 4.382$, $p < 0.038$).

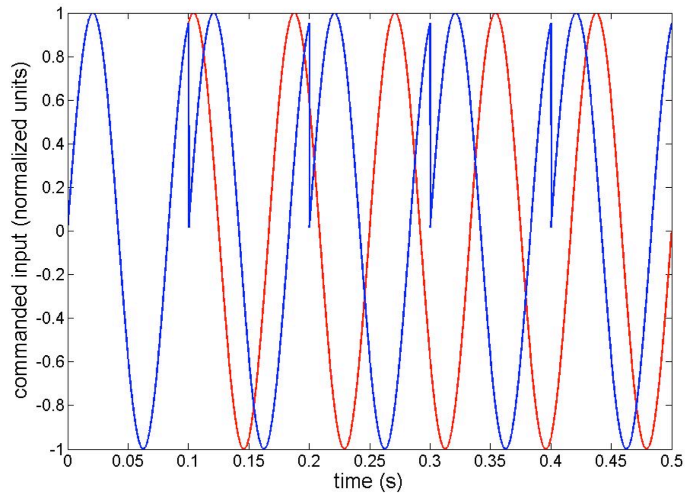
For the 10-pt group at either facility, Tukey post-hoc contrasts reveal that AB/BC transition levels were significantly higher for the two graphical formats than the text display, but that there was no difference between the PFD and OMS/MPS displays (fixed-base: $D_{\text{crit } 0.05} = 0.066\ g_{0\text{-peak}}$; centrifuge: $D_{\text{crit } 0.05} = 0.055\ g_{0\text{-peak}}$). For the 14-pt group, only the PFD and text formats differed significantly (fixed-base: $D_{\text{crit } 0.05} = 0.038\ g_{0\text{-peak}}$). However, because of the absence of a significant main effect, post hoc contrasts are not drawn for the data from the 14-pt group at the centrifuge. Thus, the general characteristic of the display effect is that the PFD and OMS/MPS formats are more immune to vibration (i.e., participants have higher thresholds for these displays), while, specifically on the centrifuge, the 10-pt text display is most susceptible to vibration (i.e., participants have the lowest thresholds for this display).

4. EXPERIMENT 2 – GENERAL POPULATION DISPLAY RATINGS AS A FUNCTION OF VIBRATION FREQUENCY/CONTENT

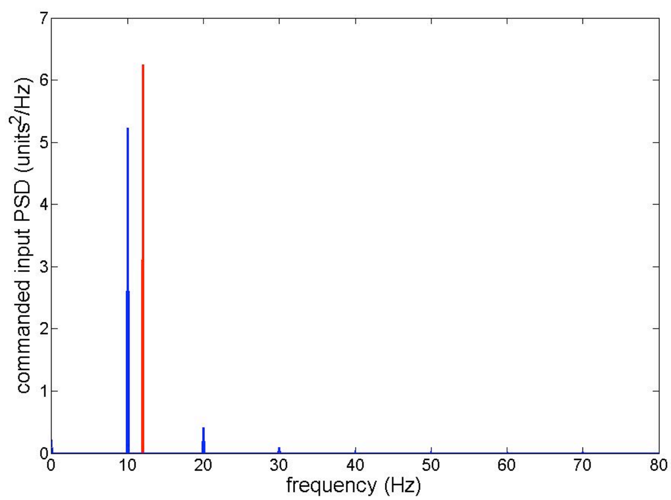
As mentioned in the introduction, the two text reading studies recently completed at Ames (Adelstein et al., 2008a, 2008b) specifically examined interactions between the anticipated 12-Hz Ares-Orion launch vibration and text-font size. The goal of those studies was to assess human reading (and processing) capability for both alphabetic and numerical text strings in the presence of vibration at 1.0 and 3.8-G bias loading. Our original plan for Experiment 1 was to examine subjective ratings of graphical displays under identical environmental conditions (i.e., 3.8-G loading plus 12-Hz vibration).

However, during a post-experiment analysis of Experiment 1, we observed a corrupted vibration waveform. Rather than the intended single-frequency 12-Hz input, the corrupted waveform introduced a 10-Hz fundamental with 20- and 30-Hz harmonics as the vibration stimulus. This corruption was due to an internal sampling buffer that truncated the command input after 100 ms and then reinitialized the buffer. As can be seen, the desired 12-Hz vibration command is initiated properly, but 100 ms into the sequence (and at every subsequent 100 ms interval), the pattern is interrupted and restarted (Figure 4.1.a, blue line) instead of maintaining the original 12-Hz signature (red line). The frequency content of the command input to the chair, expressed in normalized command-input-units-squared-per-Hz, is shown by the power-spectral density plot in Figure 4.1.b. Rather than energy focused at 12-Hz (red line), the corrupted waveform (blue line) has its dominant energy at 10 Hz, with harmonic remnants at 20 and 30 Hz that respectively have 1/13 and 1/54 the power of the fundamental.

For pure, single-frequency components, these relative densities indicate that the 20- and 30-Hz components theoretically have approximately 29% and 14% of the fundamental's amplitude in the time domain. While the vibration waveform measured by chair accelerometer closest to the participants' head generally could be decomposed according these theoretical ratios, the two harmonics can still comprise a larger proportion of the fundamental amplitude, likely dependent on the coupled biodynamical response of the chair and its occupant. Moreover, for a given occupant, there was also a slight variation with the ramp vibration profile's instantaneous amplitude. Finally, there were also slight differences in relative harmonic component amplitudes between the fixed-base and centrifuge vibration chairs. While a detailed investigation of the vibration chairs' harmonic content is beyond the scope of the present report, inspection of ramped vibration profile samples from a number of centrifuge and fixed-base chair participants indicates that the first and second harmonics, respectively, ranged between 30-50% and 10-20% of the fundamental component's amplitude.



(a)



(b)

Figure 4.1. Complex 10-prime (blue) and pure 12-Hz (red) waveforms, plotted in time-domain (a) and frequency-domain (b)

It was acknowledged in the historic 1963 centrifuge-plus-vibration dial-reading (Clarke et al., 1965) and pilot-rating studies (Vykukal & Dolkas, 1966) targeted to address potential human performance concerns arising from the POGO oscillation anticipated for Gemini's Titan-II launch system that the oscillatory test seat inputs were similarly subject to substantial harmonic distortion, resulting in accelerations not only at the desired11-Hz fundamental frequency, but also in significantly more substantial content at each of the 33- and 55-Hz components. In fact, for the critical 0.3 $g_{0\text{-pk}}$ level tested by (Vykukal & Dolkas, 1966) upon which the 0.25-$g_{0\text{-pk}}$ Gemini and Apollo 11-Hz vibration limit was founded, Clarke et al. (1965, Figure 1) reported that the two harmonics each superimposed an additional ~70% in acceleration amplitude on top of the 11-Hz fundamental—i.e., the 11-Hz acceleration component comprised only 40% of the overall input vibration amplitude as measured in g's.

While our unplanned, altered waveform was not perceived to be visually or kinesthetically different from the intended 12-Hz signal by either the participants or the engineers developing the study, the question arises as to whether this novel waveform might have impacted the usability assessments differently than a pure (i.e., without higher frequency harmonics) 10- or 12-Hz sine wave. Additionally, quantification of the variability in human observer sensitivity (in terms of display usability rating) to changes in vibration frequency that may arise as a result of potential Orion-Ares thrust oscillation mitigation implementations will help ascertain the robustness of our previous human performance data. Finally, an investigation of whether frequency harmonics affect display usability ratings may enable a reevaluation of the Gemini-era findings, which were also obtained for vibration inputs that included harmonics added to the desired 11-Hz fundamental vibration frequency.

This second experiment, then, replicates the fixed-base segment of Experiment 1 with the following modifications:

1. Participants rated the usability of displays while exposed to three different vibration waveforms: a pure 12-Hz signal (what was initially planned); the corrupted 10 Hz signal (what was actually administered in Experiment 1—which we denote as the 10' or "10-prime" condition); and a pure 10-Hz signal (to determine whether any noted rating difference is due to the difference in fundamental frequency or the presence of higher-frequency harmonics). Participants were trained on the rating task under a pure 11-Hz vibration to ensure no differential practice with a test signal.
2. Participants were drawn from the general population at ARC so that they were age-matched to the Astronaut Office at JSC. Although Astronaut Office participants have greater domain expertise with cockpit-like displays, the general population participants are sufficient because we are examining the impact of the vibration signature, not the display configuration or content. Thus, so long as the participants employ *consistent* rating criteria, it is not critical that they apply criteria that are *accurate for a flight-task evaluation*.
3. For the single-frequency signals (10, 11, and 12 Hz), vibration ramped to a maximum (0-peak) of 0.77 g rather than 0.7 g. This allows us to equate the 10' signal to the single-frequency signals either in terms of 0-peak or total root-mean-square (RMS) power.
4. Participants rated both the 10-pt and 14-pt numeric displays to ensure we had comparison data for both displays. The Astronaut Office participants in Experiment 1 rated only the one numeric display (either 10-pt or 14-pt) that they viewed in the number reading task (Adelstein et al., 2008).

Method

Participants.

Twelve members of the ARC general population who participated in earlier vibration studies (Adelstein et al., 2008a, 2008b) agreed to complete this study. There were 8 men and 4 women, ranging in age from 35 to 53. All had normal or corrected-to-normal binocular vision and had been medically cleared for vibration platform studies (see Appendix I for selection criteria). Although not present during the testing sessions, the medical monitor was on-call should any issues arise. None were noted and all test sessions were completed without incident.

Stimuli.
The displays were the same as in Experiment 1. Because participants were presented with both the 10-pt and 14-pt numeric display formats, they each viewed and rated a total of four displays rather than three.

Four vibration waveforms were used in this study. Three of these were single-frequency sinusoids: 11 Hz for the training/practice session, and 10 and 12 Hz for the test session. The fourth signature is the more complex pattern described above (i.e., the signal depicted in Figure 4.1.b). This 10' signature results in a fundamental 10-Hz signal with harmonics every 10 Hz (i.e., at 20 Hz, 30 Hz, etc.), with 99% of the signal's total power captured by the fundamental and first two harmonics.

Procedure.
The training procedure was the same as for the fixed-base sessions of Experiment 1. Because all participants were familiar with the vibration platform from previous studies, we omitted the vibration-only familiarization segment. The three training blocks were conducted with a pure 11-Hz vibration to ensure the participants would not have additional exposure to any of the test vibration signals. All blocks (both training and testing) comprised four trails (vibration ramps) because participants were rating both the 10-pt and 14-pt numeric displays in addition to the PFD and OMS/MPS displays.

Each trial was composed of a 54-second triangular ramp or envelope that modulated the amplitude of the single-frequency (10-, 11-, or 12-Hz) or complex (10-prime) waveform. Each block comprises four of these triangular ramps (one for each of the four displays), presented in succession as illustrated in Figure 4.2. Note that in all cases, as shown in Figure 4.2, the x-axis chair vibration was additively superimposed upon the background 1-G_x bias that is due to the semi-supine orientation of the chair occupant. For the single frequency sinusoidal vibration conditions (10, 11, or 12 Hz), each vibration triangle started from ~0.2 g (0-peak) and the vibration amplitude linearly increased for 27 s at a rate of ~0.02 g/s until it reached its maximum, ~0.77 g (0-peak). After reaching this maximum, the vibration amplitude then linearly decreased for 27 s at a rate of -0.02 g/s until it returned to ~0.2 g. The vibration dropped to zero for 1 s before the next trial began. For the 10-prime waveform, the amplitude of the 10-Hz fundamental sinusoid was modulated between ~0.2 and ~0.7 g (0-peak). This was to ensure that the cumulative RMS power of the single frequency sine waves (i.e., 0.77 g/1.414 = 0.55 g) was equal to the cumulative RMS power of the 10-prime signal up to its 30-Hz harmonic (i.e., 0.7g/1.414 = 0.50g at 10 Hz, with an addition 10% power at the 20- and 30-Hz harmonics).

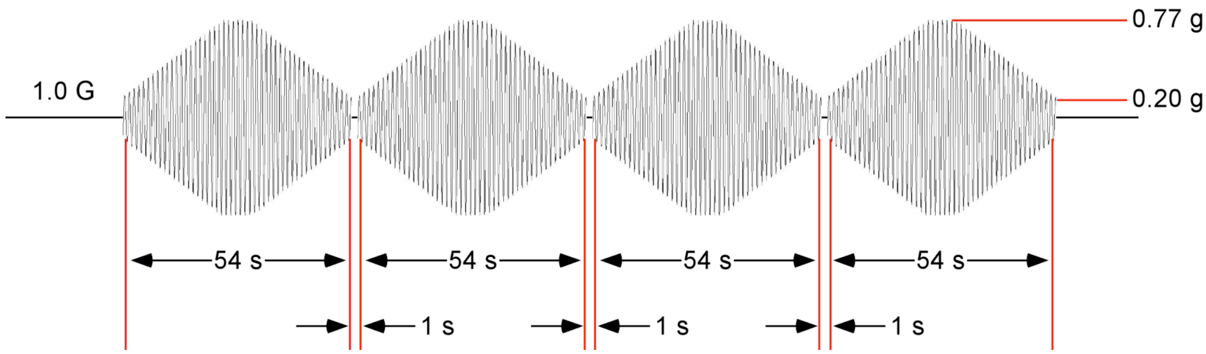


Figure 4.2. A single block sequence of four trials (one vibration ramp per display). The peak g-level for the 10' signal was reduced to 0.7g to compensate for the power in its harmonics.

The duration of each block of four trials was ~4 minutes, with an average vibration exposure of 0.45 g over this period. After the fourth trial in each block, there was an inter-block vibration-free recovery period of 5-minutes duration, which could be lengthened at the discretion of either the participant or the study principle investigator; a longer break (~15 minutes) following the 6th block of trials. Participants performed three repetitions of the four-trial blocks for each of the vibration waveform conditions, including the 11-Hz training condition. The total duration for the 12 blocks, including inter-block breaks, was ~90 minutes.

All participants completed three blocks of the 11-Hz vibration training condition first. Participant then completed three-block repetitions of the three remaining vibration conditions. The order of these nine remaining blocks was randomized across participants. Within each block, the order of the four displays was likewise randomized across participants, with the constraint that the two numeric displays (10-pt and 14-pt) were not presented in succession. Each participant retained his or her assigned display order across all training and test blocks.

Results

Transition-level button responses were processed in the same manner previously described for the Astronaut Office study (Experiment 1), resulting in single vibration estimates from each participant for the AB and BC transition levels for each of the display formats they observed under each of the vibration conditions. Thus, each participant generated two (i.e., AB and BC) transition levels for 12 experiment conditions (4 display types X 3 test vibration waveform levels). A repeated-measures ANOVA revealed significant main effects for all three factors (transition level: $F_{1,11}$= 435.8, $p < 0.0001$; display type: $F_{3,33}$= 13.54, $p < 0.0001$; and waveform: $F_{2,22}$= 4.786, $p < 0.02$) plus a significant interaction between transition level and waveform ($F_{2,22}$= 6.425, $p < 0.006$). There were no significant interactions involving display type.

Figure 4.3 shows participants AB and BC transition levels for the 10-prime waveform plotted against their corresponding transition levels for 12-Hz pure sine waveform. Because participants rate four displays, each participant contributes four AB and four BC vibration level data points to the plot. A principal component regression (i.e., the eigenvector covariance matrix for the 10-prime and 12-Hz data) constrained to pass through the origin (i.e., $y = 1.056x + 0$) was computed from the 12 data points obtained by averaging the eight observations (2 transition levels X 4 displays) per participant.. The slope of this regression indicates that, for a given display type, a given AB or BC transition level judgments would be, on average, 1.056 times higher when performing under pure 12-Hz sinusoidal vibration than under the 10-prime composite waveform. In other words, participants were, on average, 5.6% less sensitive to 12-Hz than 10-prime vibration for the given RMS amplitude at their AB and BC transition judgments. The Pearson correlation coefficient ($r = 0.489$) from the 12 independent observations indicated significant correlation between transition-level judgments for the two waveform conditions ($t_{12} = 2.628$, $p < 0.008$, one-tail). Additionally, a bootstrap parameter-free distribution of regression slopes (estimated by re-computation of the principle-component eigenvector for each of 10^5 re-samplings of the original 12 data-point pairs) was used to test the difference between this and subsequent best-fit slopes from unity. This bootstrap analysis showed that the difference between the 1.056 slope and unity is significant ($p < 0.01$). Thus, even though participants were only slightly more sensitive to the combined effect of the 10-prime waveform's frequency and harmonics than the pure 12 Hz sinusoidal input, it is confirmed statistically that this increase was significant.

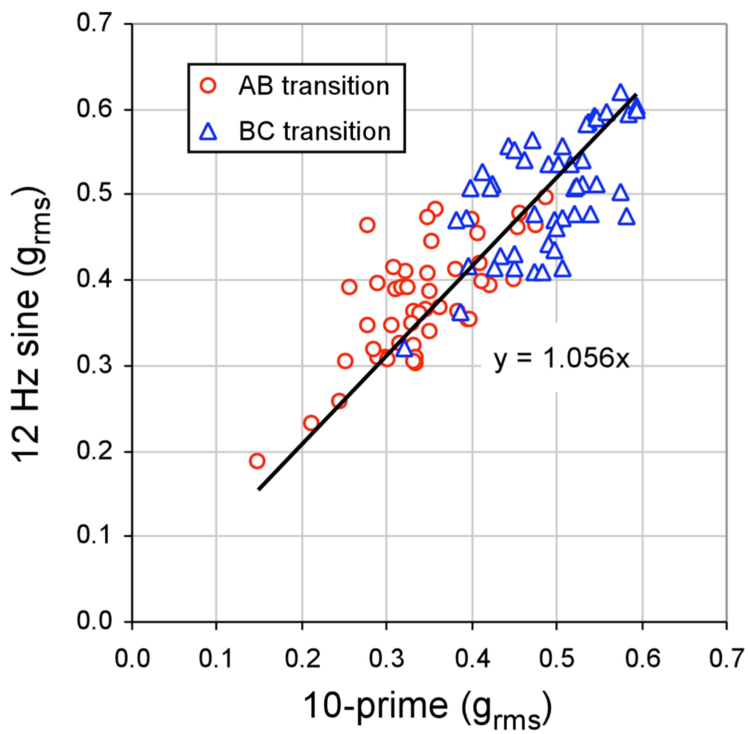


Figure 4.3. Cross-plotted 12-Hz (y-axis) and 10-prime (x-axis) AB and BC transition judgment vibration levels and best-fit principal component regression constrained to pass through the origin (0,0).

This relatively small 5.6% increase in observer tolerance to 12-Hz purely sinusoidal vibration versus the 10-prime waveform's composite of 10-Hz fundamental plus higher harmonics is a fortuitous consequence of the combination of two competing effects. As shown in the left panel of Figure 4.4, stripping out 10-prime's higher harmonics diminishes observer tolerance to the same total RMS vibration level by 3.7% (regression $y = 0.963x$; $r = 0.398$; $t_{12} = 2.033$, $p < 0.03$, one-tail); that decrease is statistically significant (i.e., different than unity slope, $p < 0.01$, bootstrap distribution 10^5 re-samplings of the 12 data-point pairs). That is, the purely sinusoidal 10-Hz energy added to compensate for the absent higher frequency (20 Hz, 30 Hz, etc.) harmonics of the 10-prime waveform leads to an earlier reduction in tolerance because higher vibration at the fundamental frequency occurs for the 10-Hz waveform. Simply stated, observers were more sensitive to the effects of vibration at the 10-Hz fundamental frequency than for equivalent RMS accelerations at the higher frequency (≥20 Hz) harmonics. As shown in the right panel of Figure 4.4, transition levels were 9.6% higher for pure 12-Hz than for pure 10-Hz vibration (regression $y = 1.096x$; $r = 0.800$; $t_{12} = 6.264$, $p < 0.0001$, one-tail), i.e., participants could absorb on average 9% vibration at 12 Hz before indicating a comparable decrement in performance for the various display types. Again, the 1.096 slope is significantly different than unity ($p < 0.0002$, bootstrap distribution 10^5 re-samplings of the 12 data-point pairs). The product of the two regression slopes in Figure 4.4, (0.963 x 1.096 = 1.056) demonstrates that the competing impacts of removing the 10-prime's higher harmonics and then converting from 10- to 12-Hz pure vibration can be viewed as processes that together result in the observed scaling of participant tolerance (or, conversely, sensitivity) between the 10-prime and 12-Hz sinusoidal test conditions.

As an alternative examination of the deleterious effect of the 20 and 30 Hz harmonics, an analysis for the 12 participants' average AB and BC transition responses for the four display formats was conducted by regressing only the 10-Hz frequency component of the 10-prime rather than its overall multi-frequency content against pure 10-Hz waveform. In this case, the regression ($y = 1.102x$; $r = 0.382$; $t_{12} = 1.94$, $p < 0.033$, one-tail) demonstrates that the inclusion of the higher harmonics in the 10-prime waveform leads to a significant (i.e., different than unity slope, $p < 0.0001$, bootstrap distribution 10^5 re-samplings of the 12 data-point pairs) 10% loss in tolerance (increase in participant sensitivity) to pure 10-Hz vibration.

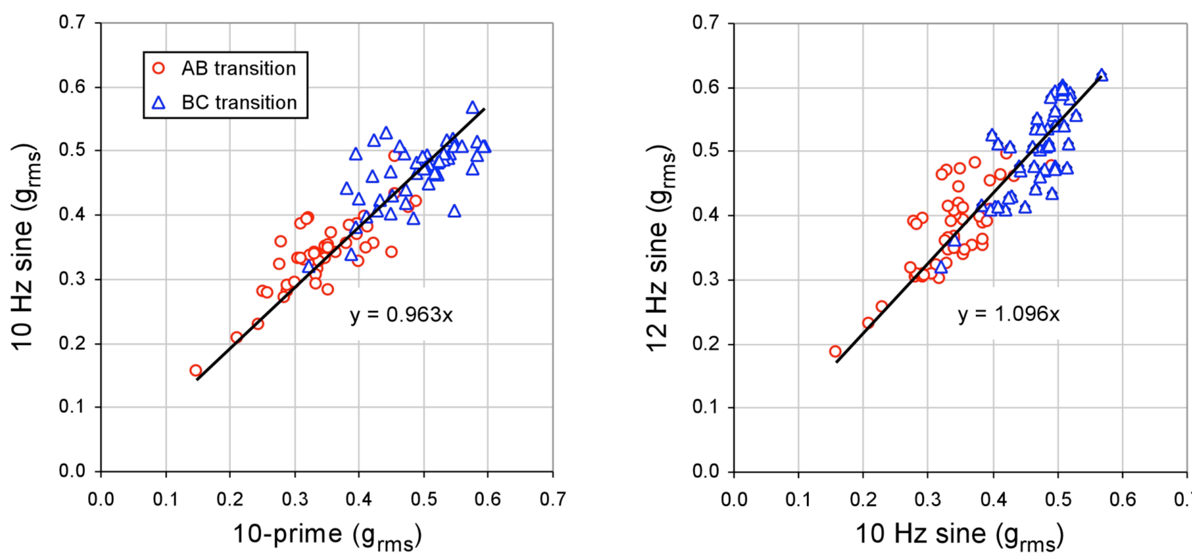


Figure 4.4. Cross-plotted 10-Hz vs. 10-prime (left) and 12-Hz vs. 10-Hz AB and BC transition judgment vibration levels and best-fit principal component regressions constrained to pass through (0,0).

5. CONCLUSIONS

The primary purpose of Experiment 2 was to determine whether the inadvertent modification of the vibration waveform used in Experiment 1 impacted participants' display ratings. We were able to determine that the difference in ratings under the 10-prime waveform (i.e., a 10-Hz fundamental with 20- and 30-Hz harmonics) and a pure 12-Hz waveform was small (5.6%), and was consistent over display types. Furthermore, we were able to determine that this difference remained small due to the countervailing effects of the frequency shift from 12 Hz to 10 Hz (which tended to decrease raters' transition levels) and the diversion of the signal's energy from the fundamental to higher-frequency remnants (which tended to increase raters' transition levels).

Given the ability to adjust transition levels for vibration signal content from the 10-prime condition, we are then able to express the findings in Experiment 1 in corrected 0-peak units that reasonably predict participants' ratings for 12-Hz vibration. These converted transition levels are shown in Figure 3.9 for the graphical displays (PFD and OMS/MPS) and Figure 3.10 for the text displays (10-pt and 14-pt fonts). Properly adjusted, we can see that graphical displays are as or more robust to vibration environment than 14-pt text displays, and significantly more robust than 10-pt text displays. The small-font displays are especially vulnerable to vibration under G-load. Depending on the type of display, we note for the centrifuge that participants on average begin to note a decrement in display usability (i.e., AB transition) at levels equivalent to between 0.33 and 0.42 g for pure 12-Hz vibration.

Our finding in Experiment 2 that display usability tolerance to pure 10-Hz vibration was diminished by ~10% with the inclusion of higher frequency harmonics has immediate implications for the 1963 centrifuge-plus-vibration test data supporting the historic Gemini and Apollo vibration specifications for crew performance. Effectively, this finding suggests that Clark et al.'s (1965) and Vykukal and Dolkas's (1966) procedure for extracting the fundamental component from their multi-frequency vibration content understates the equivalent vibration required from a pure sinusoid to produce the same performance decrements. Although neither Clark et al (1965) nor we examined phase relations between the different frequency components, one could speculate that the equivalent effects observed for Vykukal and Dolkas's (1966) 0.30 $g_{0\text{-peak}}$ "derived" vibration input would actually be equivalent to a level 10% (or more higher) had their vibration had been delivered as a pure 11-Hz waveform. Thus, in 1963, NASA might have instead selected a slightly higher 11-Hz vibration limit for crew performance.

These usability ratings are consistent with the objective reading performance results reported in Adelstein et al (2008b). In the number reading data (collected under 3.8 G), statistically significant performance decrements for the 10-pt display were observed at vibration levels of 0.5 and 0.7 $g_{0\text{-peak}}$, but not the lower ones. For the 14-pt display, significant reading decrements were only observed at 0.7 g. Figure 5.1 superimposes the prior objective reading data (error rates and response times) on the AB and BC transitions obtained for the same 10- and 14-pt font-group participants. As shown in Figure 5.1, the average BC transitions (10-pt: 0.430±0.048 g; 14-pt: 0.535±0.034 g) precede the vibration levels at which objective reading performance was significantly hampered for either font size. The AB transitions, at which display usability begins to be compromised, begins at or above 0.3 g (10-pt: 0.326±0.033 g; 14-pt: 0.392±0.032 g).

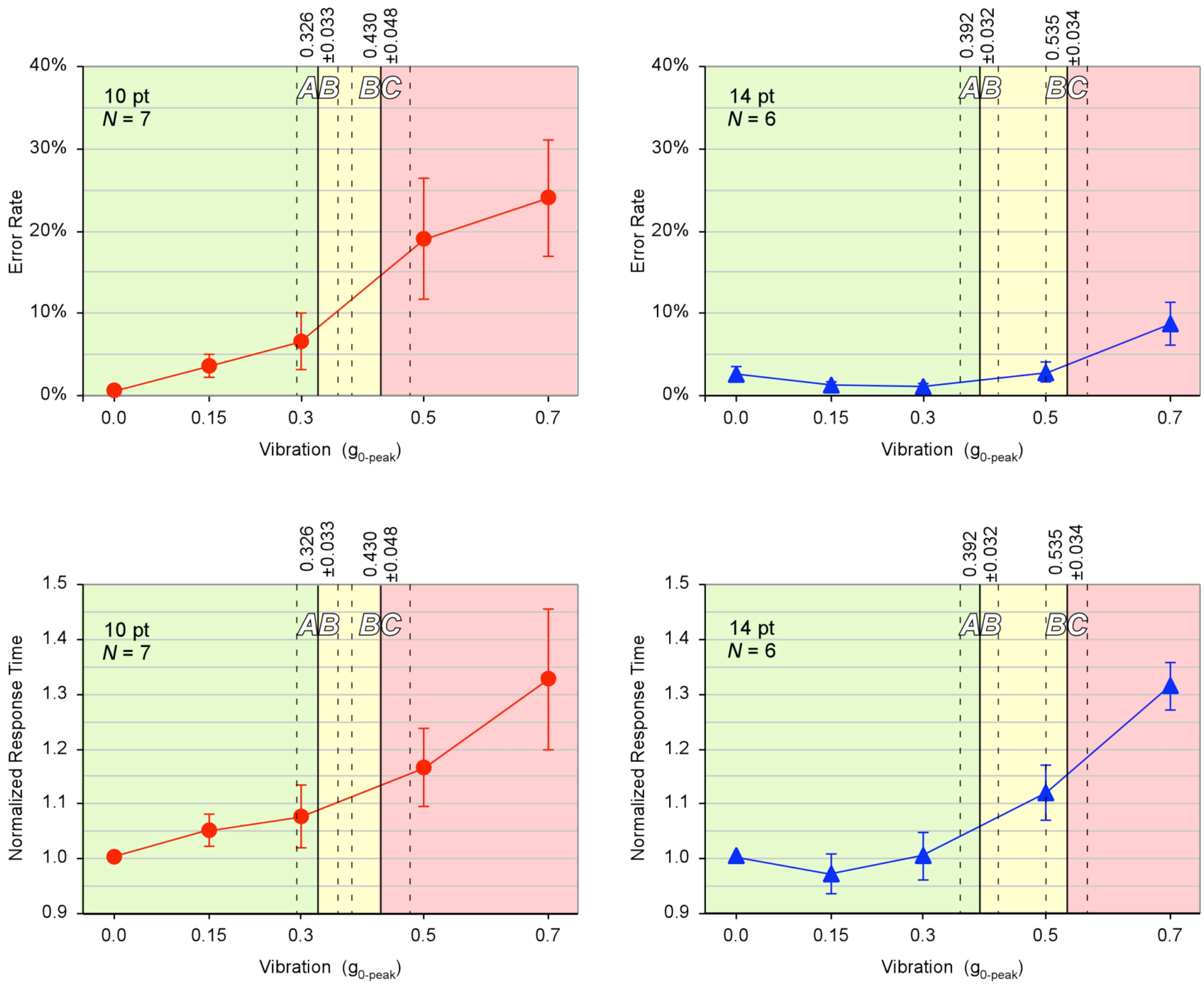


Figure 5.1. Performance on the number-reading task, from Adelstein, et al. (2008) overlaid with A-B and B-C transition levels from current study. Error rates (top row) and response times (bottom row) are shown separately for 10- and 14-pt display Astronaut Office participant groups. Vertical error bars are ±SEM; vertical dashed lines on either side of green-yellow-red color boundaries indicate ±SEM of judged AB and BC transition levels.

To further investigate whether usability ratings are related to objective measurements of reading performance for the same displays, Spearman correlations-by-rank between AB/BC transitions and reading task error rates and response times reported previously (Adelstein, 2008b) were computed from the 13 participants in both studies. As shown in Table 5.1, correlations of individual participants' AB and BC transitions with their reading task error rates at either 0.5 or 0.7 g were significant; correlations of AB and BC transitions with their reading task response times were not. Thus, in this case, judged display usability, regardless of transition level, is generally seen to reflect only the error rates associated with the information extraction task. The absence of significant correlation between judged usability and reading task response time (or between reading task error rates and response time) at 0.5 and 0.7 g vibration levels indicates that response speed is not a determining factor in judged usability (or error rate) for these particular 10- and 14-pt displays.

Table 5.1 Correlations-by-rank between participant rating thresholds and reading performance (N = 13 participants)

		Reading Task			
		Error Rate		***Response Time***	
		0.5 g	0.7 g	0.5 g	0.7 g
Rating Task	***AB***	-0.608**	-0.630**	0.236	0.082
	BC	-0.534*	-0.556*	-0.006	-0.066

* $p < 0.025$; ** $p < 0.05$

Finally, we observed in Experiment 1 that usability ratings were influenced by G-loading, with vibration thresholds being reduced (or, equivalently, participant sensitivity being increased) by an average of 11% at 3.8-G bias on the centrifuge when compared against the 1-G bias on the fixed-base chair. This G-induced decrement was most profound (~25%) for the 10-pt numerical display, the font-size seen in our prior reading study (Adelstein et al., 2008a,b) to be less robust to vibration. Because the decrement in self-rated vibration tolerance caused by the 3.8-G bias depended on the specific display type, caution must be exercised in attempting to extrapolate findings from fixed-base vibration platform testing. While the display usability rating and numerical reading part-task environments are useful for initial evaluation and definition of the vibration-performance trade space, it will prove critical to validate the findings in high-fidelity simulations that emulate flight conditions as closely as possible.

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Appendix I: Participant Selection Criteria for Experiment 2

- 12 men or women, 35 to 55 years of age
- Normal or corrected-to-normal vision in both eyes (cannot wear multi-focal or progressive lenses; we can provide reading glasses with equal correction to both eyes)
- No color-vision deficits; no strabismus; normal depth perception
- No vestibular problems or susceptibility to intense motion sickness
- No surgeries or hospitalizations within past 90 days
- No unmanaged high blood pressure (if on high BP medicine, note type and dosage); no heart disease or medication
- No history of seizures, neurological, or “nervous” disorders
- No history of spine/neck injury or disease